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Knowledge Organization and its Representation in Teaching Physics

Magnetostatics in University and Upper Secondary School Levels

Sharareh Majidi

Department of Physics
Faculty of Science
University of Helsinki
Helsinki, Finland

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Author's address

Department of Physics
P.O. Box 64
FI-00014 University of Helsinki
Finland
Sharareh.majidi@helsinki.fi

Supervisors

Docent Ismo Koponen, Ph.D.
Department of Physics
University of Helsinki

Professor Heimo Saarikko, Ph.D.
Department of Physics
University of Helsinki

Pre-examiners

Professor Jukka Maalampi, Ph.D.
Department of Physics
University of Jyväskylä

Docent Antti Savinainen, Ph.D.
Department of Teacher Education
University of Jyväskylä

Opponent

Professor Priit Reiska, Vice Rector, Ph.D.
Institute of Mathematics and Natural Sciences
Tallinn University

Abstract

Physics has been always one of the most challenging subjects to learn for university and school students. It is also considered a demanding topic for teachers who aim to teach it efficiently. Therefore, one of the most important notions in physics is to find suitable ways to maximize productive learning and teaching outcomes. One of the most important factors that influence physics learning and teaching is the organization of physics knowledge and the ability to arrange its concepts properly. In physics education, the organization of knowledge and meaningful structural patterns is a vital component of teachers' subject matter knowledge. Correspondingly, physics textbooks, teachers, and lecturers are expected to translate their subject matter knowledge with the most pedagogically effective approaches. So another central component in physics education is teachers' pedagogical content knowledge, which is about a) the most essential representation forms (e.g. analogies, models, examples, simulation) that teachers employ in the classroom, and b) students' misconceptions and difficulties as well as the best approaches to diminish those complications. This thesis examines the organization of knowledge and representation forms used by teachers and found in university and upper secondary school textbooks. Magnetostatics is recognized as one of the most challenging topics in physics, which the society of physics education has largely disregarded. In this study, we concentrate on two important magnetic laws of Biot-Savart/magnetic flux density and Ampère. These laws as well as their applications and examples are employed broadly in both upper secondary schools and universities. These topics provide us sufficient space to investigate the organization of physics knowledge as well as the most appropriate representation forms. In these studies, we utilized a variety of qualitative and quantitative methods to collect data. Different samples are selected from standard university textbooks, teachers at the University of Helsinki, Department of Physics, and some teachers from highly reputed upper secondary schools in Helsinki, Finland. To study the organization of knowledge of teachers and textbooks, their structures are first portrayed by means of concept maps. Second, structural measures are applied to evaluate any meaningful patterns detected in these concept maps. Structural measures contain complex network observables such as density of links, hierarchy, clustering, cycles, and loops. In other cases, the structural measures are confined to the number of dead-ended concepts, core concepts, incoming and outgoing links. Results reveal certain similarities and differences between the ways knowledge is organized and arranged within the subject matter of teachers or textbooks. The results report the shared concepts and structural patterns between university teachers and the textbooks they use for their teaching purposes and identify differences between the structural properties of two laws of Biot-Savart and Ampère. The rest of the results inform us about a variety of forms that could be employed to represent these laws. Recognized representation forms include experiments and demonstrations, stating facts in physics, inductive and deductive reasoning, examples, and explanations, and models such as analogies, mathematical models, and visual models are ultimately drawn from the data analysis through this research. The novelty of this thesis is its briefly examination and discussion of the possible link between the organization of knowledge, which functions as teachers' subject matter, and their representation forms, which serve as their pedagogical content knowledge. This thesis also discusses the implications for teaching and learning as well as practical applications of it.

ساختارمطالب و مفاهیم فیزیکی و صورت های مختلف ارائه در تدریس فیزیک

چکیده رساله دکترا

مبحث فیزیک یکی از چالش برانگیزترین مباحث جهت آموختن دانش آموزان و دانشجویان از یک سو و تدریس با بازدهی بالا برای دبیران و استادان دانشگاهی از سویی دگر بوده است. بنابر این چگونگی آموزش، فراگیری و تدریس فیزیک به صریحترین و مفیدترین نحو، از اهم موضوعات مطرح درآموزش علوم میباشد. یکی از مهمترین عوامل تاثیر گذار در آموزش و تدریس فیزیک، چگونگی سازمان دهی و چیدمان منطقی مطالب و مفاهیم فیزیکی توسط دبیران یا استادان و نویسندگان کتب مدارس و یا دانشگاهی میباشد. در آموزش فیزیک از این بخش از دانش مدرسان یا مولفان فیزیک، به عنوان **دانش موضوع محور** (دا مو م) نام برده می شود. به طور کلی، انتظار میرود که کلیه عوامل مداخله کننده در آموزش فیزیک از قبیل دبیران، استادان، نویسندگان کتب راهنما و یا مراجع فیزیکی، قابلیت بیان مطالب و مفاهیم فیزیکی را به نحو معنادار و منطقی دارا باشند. دگر عامل موثر در آموزش فیزیک بکارگیری روشهای مناسب و تاثیر گذار برای بیان کردن مطالب و مفاهیم فیزیکی میباشد که **دانش مربوط به محتوی و روشهای آموزشی علوم** (دا م رآ) نامیده میشود. در این رساله انواع مختلف این روشها و ساختارها مورد بحث قرار گرفته است. مبحث مغناطیس از جمله مباحثی در فیزیک آموزشی میباشد که کمتر از سایر مباحث مورد توجه قرار گرفته است. ما در این رساله به بررسی دو قانون پر اهمیت و کلیدی در مغناطیس بنام قانون بیوت-ساوارت و قانون آمپر می پردازیم. این قوانین از دشوارترین قوانین فیزیک پایه نه تنها در سطح دبیرستان، بلکه در مقاطع دانشگاهی نیز میباشد. به همین علت انتخاب این دو مبحث به ما فضای کافی برای تحقیقات و تجزیه و تحلیل سازمان دهی و چیدمان منطقی مطالب و مفاهیم فیزیکی از یک جهت و بکارگیری روشهای مناسب برای بیان کردن مطالب و مفاهیم فیزیکی در مقاطع دانشگاهی و دبیرستان از جهت دیگر را میدهد. در این رساله از طرق و اسلوب متفاوت آموزشی برای جمع آوری داده های مورد نیاز استفاده گردیده است. نمونه های مراجع فیزیک از انواع کتب بین المللی فیزیک، نمونه های استادان دانشگاهی از دانشگاه هلسینکی واقع درکشور فنلاند، و سرانجام نمونه دبیران از دبیرستان های فنلاند برگزیده شده است. برای به تصویر کشیدن چیدمان مطالب و مفاهیم فیزیکی (مربوط به قوانین بیوت-ساوارت و آمپر) در محتوای علمی برنامه درسی دبیران و استادان و کتب مرجع فیزیکی، از نگاشت مفهومی و برای تحلیل آنها از انگاره یا الگوی ساختاری استفاده شده است. سپس تفاوت بین انگاره های ساختاری توسط کمیت های اندازه گیری در شبکه های پیچیده و یا تحلیل حلقه های مفهومی، تجزیه و تحلیل گردیده است. نتایج به دست آمده از تفاوت های اساسی در مضمون کتب مرجع و دانش موضوع اصلی استادان دانشگاهی سخن میگوید. علاوه بر این مقایسه ساختار مفاهیم فیزیکی برای بیان قانون بیوت-ساوارت و قانون آمپر نشان میدهدکه این دو قانون مغناطیسی تفاوت چشمگیری در نحوه چیدمان و سازمان دهی دارند. باقی نتایج ما را از بکارگیری صورتهای مختلف آموزشی برای بازتاب ارتباط متفاوت بین مفاهیم مغناطیسی مطلع میسازد. کاربرد صحیح مثالها، توضیحات و تفاسیر فیزیکی و موارد آموزشی دیگر مانند بکارگیری انواع مختلف مدلهای آموزشی شامل مدلهای گوناگون ریاضی، مدلهای بصری مانند تصاویر دو بعدی و سه بعدی (ویدیوهای آموزشی و شبیه سازیها توسط نرم افزارهای آموزشی)، انجام و نمایش دقیق و صحیح آزمایشات و پدیده های فیزیکی، استدلالهای استنتاجی و استقرایی، قابلیت قیاس موضوعی و مفهومی یک مبحث فیزیکی (الکتریسیته) با مبحث مرتبط به آن (مغناطیس)، و سرانجام اشاره به وجود مسلم یک سری واقعیت های فیزیکی (بر همکنش الکتریکی و مغناطیسی) همه و همه از انواع روشهای آموزشی مورد بحث در این رساله میباشند. در این راستا اختلافات و اشتراکات متفاوت و چشمگیری بین دانش مربوط به محتوی و روشهای آموزشی نمونه های مورد بررسی گزارش شده است. در این رساله، ارتباط بین ساختار مفاهیم و صورتهای مختلف ارائه در آموزش فیزیک برای اولین بار مورد تحقیق و بررسی قرا گرفته است. در نهایت کاربرد عملی و اجرایی این رساله بیان گردیده است.

پیشگفتار

اینجانب بعد از فارغ التحصیل شدن در رشته فیزیک ماده چگال از دانشگاه شهید بهشتی و اخذ مدرک کارشناسی ارشد به منظور ادامه تحصیل خود و همسرم جناب آقای دکتر علی ذهبی راهی کشور فنلاند شدیم. علاقه شخصی من به آموزش فیزیک بعد از مطالعه مجله کوانتوم و تدریس فیزیک دانشگاهی و دبیرستان در دوران تحصیلم در ایران آغاز شد. به همین جهت من رشته آموزش و پرورش دبیران فیزیک را در مقطع دکترا در دانشگاه هلسینکی، دانشکده فیزیک، برای خود برگزیدم. این رشته نوین روز به روز در جوامع توسعه یافته بالاخص کشورهای اسکاندیناوی و ایالات متحده در حال ترویج میباشد. گروه تحقیقاتی ما در دانشکده فیزیک در عرصه های مختلف بویژه بررسی نگاشت مفاهیم، ساختار مطالب، شبکه های مفهومی، فلسفه و تاریخ فیزیک و آموزش و تکنولوژی معاصر در آموزش و پرورش دبیران فیزیک مشغول به کار هستند.

من در اوایل دوره دکترایم ۱۳۸۸ مشغول تحقیق بروی شبکه های پیچیده شدم. بدین ترتیب که مفاهیم فیزیکی توسط ندهای (گره ها) شبکه و ارتباط مفهومی بین آنها با گزاره های معنی دار گوناگونی معرفی میشود. در انتهای سال ۱۳۸۸ من در یک پروژه دانشگاهی استخدام شده و در طی آن پروژه در دانشکده فیزیک، نگاشت مفهومی جلد دوم کتاب دانشگاهی فاینمن را که درباره الکترومغناطیس و مواد است را ساخته و مورد بررسی قرار داده و خواص آن را با شبکه دیگری که متعلق به استادان دانشگاه هلسینکی بود، مقایسه نمودم.

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Helsinki, October 2013

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I. **Majidi, S.** & Mäntylä, T. (2011). The knowledge organization in physics textbooks: A case study of magnetostatics. *Journal of Baltic Science Education*, 10 (4), 285-299.

II. **Majidi, S.** (2012). Structural patterns and representation forms of university physics teachers: Biot-Savart Law and Ampère's law. *Journal of Baltic Science Education*, 11 (4), 318-332.

III. **Majidi, S.** (2013). A comparison between the knowledge organization of university physics teachers and the textbooks they use: Biot-Savart law and Ampère's law. Accepted for publication in *International Journal of Mathematics and Science Education*. DOI: 10.1007/s10763-013-9457-1
"The final publication is available at Link.Springer.com"

IV. **Majidi, S.** & Emden, M. (2013). Conceptualizations of representation forms and knowledge organization of high school teachers in Finland: "magnetostatics". *European Journal of Science and Mathematics Education*, 1 (2), 69-83.

The contributions of the author of this dissertation to the original co-authored publications:

Article **I**: The author had a central role in setting up the research design. She alone was responsible to collect and analyse the data. The author had a major role in constructing and writing of the article.

Article **IV**: The author alone was responsible for designing and planning the research, setting up the research, collecting the data. She had a central role in analysing the data, and constructing and writing the article.

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For other related publications of the author in international conferences, please see the references.

Abbreviations

SMK	subject matter knowledge
PCK	pedagogical content knowledge
ReFs	representation forms

1 Introduction

One of the key factors in physics teacher education is focusing on teachers' knowledge and its bases. Teachers' subject matter knowledge (SMK) is presumably a crucial component of teachers' knowledge. According to Shulman (1986), teachers' SMK can be described in terms of two major categories of substantive and syntactic structures. The former concerns teachers' knowledge of different concepts and their organizations in specific disciplines, whereas the latter entails scientific inquiries. This thesis focuses on the substantive knowledge of teachers' SMK. SMK encompasses the main concepts, laws, or principles as knowledge elements as well as a variety of different ways to organize them. Teachers must be aware of the essential ways to organize their SMK, which enables them to better understand and design their teaching. Expert teachers possess high-quality organized knowledge, including meaningful structural patterns (Chi et al., 1981). As a result, the necessity of having organized knowledge for expert teachers is undeniable. This notion is consistent with successful and beneficial teaching and learning (Mäntylä, 2011).

Textbooks often provide teachers and students with a conception of the organization of scientific knowledge. Textbooks are a kind of structural materials in which both students and teachers encounter academic standards. Textbooks provide teachers and students with ways of representing and organizing knowledge. Some studies have confirmed the high impact of textbooks on teachers' organization of knowledge (Koulaidis & Tsatsaroni, 1996). Despite the vast body of educational research on the influence of text-based materials on learning (Ainsworth & Burcham, 2007; Roseman et al., 2009), little research is available on the knowledge organization of textbooks.

A basic assumption behind the recognition and analysis of knowledge organization in physics textbooks or teachers' SMK is that knowledge can be analysed in terms of conceptual elements and meaningful relationships between those elements (Koponen & Pehkonen, 2010). To study the structure of knowledge, we need a suitable tool to depict and represent it. Concept maps have been employed in a variety of educational research areas as an appropriate visualization tool to represent knowledge. Besides, they allow deeper interpretations of knowledge organization (Novak & Canas, 2006). For example, concept maps serve to evaluate teachers' SMK (Ferry, 1996) or students' learning (Kinchin et al., 2000). In contrast to traditional concept maps based on propositions, this study uses a different form, where models and experiments link the concepts. After representing the organization of knowledge with concept maps, we qualitatively examined their characteristics.

This thesis portrays how university physics teachers (Articles II, III), upper secondary school physics teachers (Article IV), and university physics textbooks (Article I, III) organize their SMK with concept maps and evaluates their organizations through structural patterns.

With regard to university textbooks (Article I; Majidi, 2011), this study utilizes structural components, including hierarchy and interactive processes that resemble the approaches of Kinchin et al. (2000): hierarchy shows justifiable levels, whereas interactive processes mirror the interconnectivity of concepts.

In the case of university teachers, their organization of SMK is classified in terms of the connectivity of concepts, which are recognized by number of meaningful structural patterns such as loops or cycles on the one hand, and dead-ended concepts, on the other hand. These dead-ended concepts are disconnected from the rest of the map and diminish the connectivity of the map as a whole (Article II, Majidi & Mäntylä, 2012). After this organization, their SMK is categorized into three classes of **strongly**, **moderately**, or **loosely** connected structures.

The next article of this thesis (Article III) compares the organization of knowledge in university physics textbooks to the organization of knowledge used by university physics teachers. These teachers often refer to the textbooks studied in Article I for teaching purposes, such as teaching instructions and plans. It is therefore worth investigating similarities and differences between teachers' organization of SMK and that in textbooks. Article III employs two approaches for measuring the organization of knowledge: a) the hierarchical nature of knowledge organization as a sign of the logical organization of knowledge and of sequencing SMK, and b) clustering structures as an indication of the interconnectivity of concepts. These two approaches serve to compare the organization knowledge of teachers and textbooks.

Finally, the organization of knowledge of upper secondary school physics teachers (Article IV, Majidi & Emden, 2013) is examined by focusing on teachers' priorities for selecting concepts, which presumably reflects teachers' views about the ordering of concepts. Besides, the concept maps that teachers construct are evaluated by considering the most relevant core concepts (concepts with the most attached links) as well as incoming and outgoing links to/from the core concepts, a method previously suggested by Kinchin (2000).

Second part of this thesis focuses on teachers' pedagogical content knowledge (PCK). According to Shulman (1986, 1987), PCK embraces teachers' knowledge of a) representations such as different analogies, examples, and explanations and b) students' difficulties and misconceptions as well as strategies to conquer them. The literature review reveals that most researchers have focused on the second category of PCK, as mentioned above (Abell, 2007). Many studies of PCK have been carried out since Shulman (1986, 1987) introduced the concept. Scholars either added or modified the categories of teachers' PCK and sometimes even their knowledge bases (Parker & Oliver, 2008; Magnusson et al., 1999; Hashweh, 2005; Loughran et al., 2004; Rollnick et al., 2013). In this study, however, we stick to Shulman's notion of teachers' PCK: teachers should be able to represent their SMK in a way that is pedagogically effective and comprehensible for their students. The representation and formulation of teachers' SMK appear to be crucial in their PCK. This thesis has focused a great deal of interest on the representation forms (ReFs) that teachers use to translate their SMK. Article II uses interviews to investigate teachers' ReFs as a part of their PCK to formulate their SMK and describes the categories of ReFs and frequency of use of these forms that emerged from analysis of the content of the interviews. These forms can also be interpreted as the nature of links between concepts. Article IV infers ReFs by expressing teachers' opinions through online questionnaires. Deeper information comes from observations of teacher's lessons.

Article I studied textbooks by qualitatively interpreting the nature of the links between concepts through some well-established questionnaires and reports on categories of the nature of the links in textbooks. The results show that categories of the links in textbooks are consistent with teachers' ReFs.

The final stage of this thesis examines the possible interplay between the organization of knowledge, as a part of teachers' SMK on one hand, and their ReFs, as a part of their PCK, on the other (Articles II & IV). It is important to mention that we did not investigate whether teachers' SMK and PCK are distinct or whether one evolves from the other (cf. Hashweh, 2005; Magnusson et al., 1999). Rather, we state that the organization of knowledge is based on their SMK and relatively on their PCK. Article II briefly reports on the relationship between ReFs and teachers' organization of knowledge, and Article IV briefly discusses the place of ReFs and OrgK in teachers' PCK and SMK. A summary of different stages of this thesis appears in Fig 1 below:

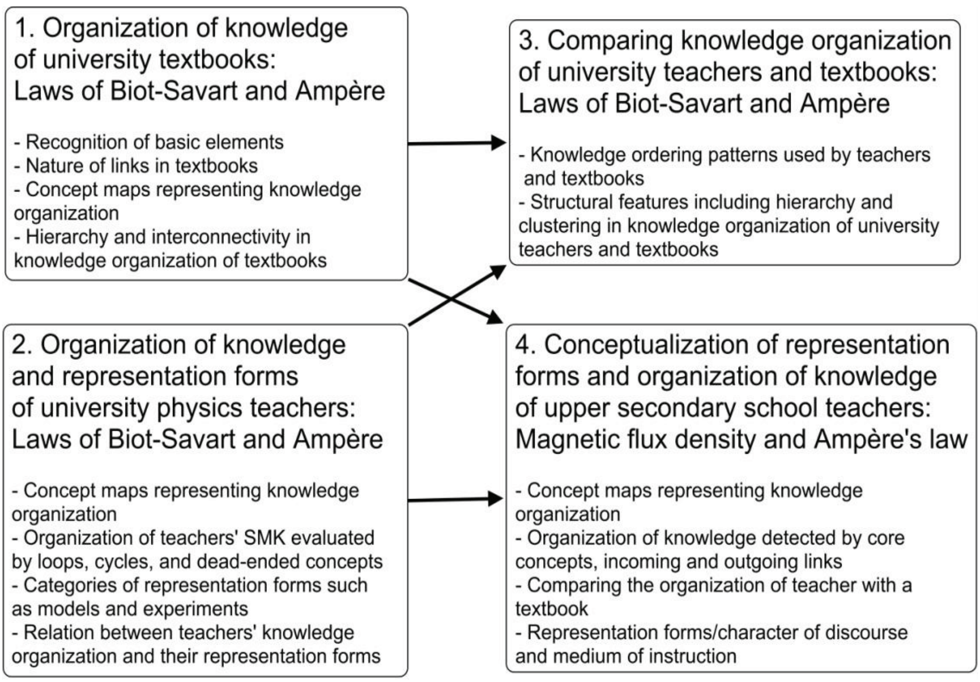

Figure 1 *Different stages of studies conducted through this thesis. Links show the logical relations between stages.*

2 Organization of knowledge

Knowledge is more than a mere collection of conceptual elements such as facts, principles, and formulas. One approach to understanding how knowledge has been formed is to examine its structure and organization. This allows us to realize how conceptual elements of knowledge are tied together or ordered. In addition, acquiring more information about the ways in which knowledge is constructed provides us reasonable grounds for justifying knowledge. In this regard, Chi et al. (1981) posited that knowing more means possessing organized knowledge. Therefore, possessing organized and structured knowledge shapes learners' thinking about a subject.

The organization of knowledge also influences one's teaching, learning, and understanding of science. Possessing organized knowledge and meaningful structural patterns has been discussed in a variety of domains, including science education, and its impact has been debated in the context of teachers' SMK, learners' problem solving, the development of experts' knowledge, and coherent text-based materials (Bransford, Brown, & Cocking, 1999). Likewise, understanding how scientific knowledge is organized in study materials such as textbooks is essential. Teachers and students most often refer to textbooks in order to "meet the standards" (National Education Goal Panel, 1998). Because textbooks mirror a variety of approaches to organizing conceptual elements apprehending the structure of concepts in the content of textbooks provides teachers and learners with ideas with which to order their own SMK for their teaching plans and instructions. This thesis investigates the organization of both the SMK of teachers (Articles II, III, & IV) and the content knowledge of textbooks (Articles I & III).

Examining the organization of knowledge requires a discussion of its properties. Concept maps have been recognized and utilized as appropriate tools for visualizing and representing the organization of teachers' SMK (Ferry, 1996; Rollnick et al., 2013), evaluating students' understanding (Kinchin et al., 2000; Hay et al.; 2008), and applying it as a research tool for improving science education (Van Zele et al., 2004). The concept maps here serve to represent and show the organization of knowledge of either textbooks or teachers (Articles I-IV). The organization of knowledge, as visualized by concept maps, can be captured by concepts, links between concepts, and the structural outlook of maps. This originates from our central assumption behind recognizing the organization of knowledge, which we can examine in terms of conceptual elements, different categories of links, and different patterns (Chi et al., 1981; Kinchin et al., 2000; Hay et al., 2008).

2.1 Organization of subject matter knowledge of physics teachers

Teachers' SMK has been recognized as an essential component of their knowledge. Shulman (1986, p. 9) argued that "to think properly about knowledge requires going beyond the knowledge of facts or concepts of a domain. It requires understanding the structure of the subject matter." The way in which teachers organize and structure the concepts appears to play an important role in teachers' SMK. Abell (2007) reviewed the literature about the SMK of science teachers in different disciplines of science: chemistry, earth and space science, biology, and physics. Of the studies focusing on SMK, several are about physics: "By far the most research on teachers' SMK in science has taken place in the domain of physics" (Abell, 2007, p. 1116). These studies show that a great deal of interest focused on teachers' misunderstandings, which were drawn from students or teachers' understanding of specific concepts. So, according to Abell's report (2007, p. 1117) "understanding how physics teachers understand the relation among concepts remains a largely unmapped field of study." This thesis aims to fill this gap by studying the organization and structure of SMK of teachers in university (Articles II & III) and in upper secondary school (Article IV).

2.2 Organization of physics textbooks

Textbooks as resources for curriculum provide teachers and learners certain ways to organize and arrange their knowledge. Although textbooks most often repeat the author's decisions and views about the optimal ways to arrange the knowledge presented, useful applications of textbooks in science education are nevertheless undeniable (Ball & Cohen, 1996; Davis & Krajcik, 2005). However, studies of the organization of knowledge in textbooks are relatively rare (see Koulaidis & Tsatsaroni, (1996) for an exception). Instead, plenty of research has examined coherent text-based materials and studied their impact on teaching and learning (Ainsworth & Burcham, 2007; McKeown et al., 1992; Roseman et al., 2010). Roseman et al. (2010) argued that one of the main goals of high-quality textbooks is to help learners – and even teachers – to realize the important connections between concepts. Investigating the organization of knowledge is as important as studying the coherence of text-based materials. Thus far, however, researchers have analysed the content of textbooks mostly from perspectives of the science, technology, and social aspects of textbooks (STS); science as a body of knowledge, thinking, and investigation (Orpwood, 1984; Chappetta et al., 1993; Wilkinson, 1999); and literacy properties (Strube, 1989). However, in this study emphasis falls on organizing the content knowledge of textbooks, how concepts are arranged, what kinds of categories of links connect the conceptual elements, and, finally, how structural patterns can be visualized and examined (Articles I & III).

2.3 Nature of links in the organization of knowledge

Conceptual elements include concepts, principles and laws, all of which are connected to each other through different types (or categories) of links (Articles I, II, & III). These categories represent the existence and nature of links. In Articles (I, II, & III), the nature of links differ from that of the traditional verbs (Novak & Govin, 1987) and can be captured by different models and experiments, which have been broadly studied elsewhere (Mäntylä, 2011). As Jauhiainen (2013) noted, science education uses different types of experiments, such as formal, discovery-oriented, perception, and generative experimentation: “according to generative experimentation, the role of theory becomes more important in the following steps of producing knowledge where theory serves as a means of organizing (the) dependencies found in experiments” (Jauhiainen, 2013, p. 17). This thesis focuses on the organization of knowledge inferred through generative experiments (Koponen & Mäntylä, 2006), even though other types of experiments may have been possible.

The types of models discussed here (Articles I, II, III) are inspired by following notions:

- **Visual models** such as figures and diagrams have the potential to express the relationships between conceptual elements and to improve one’s understanding of the concepts (Gilbert, 2005).
- **Mathematical models** are a part of physics knowledge and describe/explain the mathematical relationships between conceptual elements through formulas or equations (Van Heuvelen, 1991).
- **Analogy** links similar concepts to each other in different subjects (Glynn & Takahanshi, 1998).
- **Reasoning** justifies the connections between concepts (Brachman & Levesque, 2004).
- **Statement of fact** is simply an explicated fact.

The position of a **statement of fact**, compared to other categories, appears to be ambiguous. However, since it concerns declarative knowledge such as observation, discoveries, and phenomena, we could take it as a model.

In summary, either model-based or experimental links feature the nature of links through the concept maps of teachers (Articles II & III) and textbooks (Articles I & III).

3 Structural patterns of knowledge

The organization of knowledge can be depicted through concept maps. Several approaches are available to assess the organization and structures of knowledge. For example, Kinchin et al. (2000) employed a qualitative method to study students' concept maps in terms of structural patterns, including basic network-, spoke-, and chain-like structures. In their studies, these structures mirrored students' understanding of some topics in biology. Thus, we surveyed structural patterns according to the following four types:

1. **Interactive process and hierarchical structures** (Article I). Interactive processes indicate the association and interconnectivity between conceptual elements. This can be examined through the numbers of cross-links between concepts and numbers of incoming and outgoing links. On the other hand, hierarchy emphasizes that justifiable levels of knowledge and can be expressed as a weighted sum of connections within a given level (Kinchin et al., 2000; Hay et al., 2008; McClure et al., 1999).

2. **Numbers of dead-ended concepts as well as loops and cycles** (Article II): Dead-ended concepts that are disjointed and unattached to the rest of map. They usually contain only one incoming or outgoing link, and thus lower the connectivity of structure (Mäntylä, 2011). The numbers of loops and cycles show the connectivity of concepts and mirror constructions of interwoven structures where concepts tie together.

3. **Hierarchy and clustering** (Article III): hierarchy corresponds to what was noted above. However, Article III describes hierarchy in terms of a particular motif (spoke) and focuses on the degree of the overarching hierarchy of knowledge. Clustering shows the degree of connectivity of knowledge and is described in terms of specific motifs (triangles) (da Costa et al., 2007).

4. **Incoming and outgoing links to core concepts as well as the core concepts themselves** (Article IV): Core concepts are central among the other conceptual elements because of the numerous links that connect them. Both outgoing and incoming links are directly connected to concepts. However, the direction of incoming links is inwards the concepts, whereas outgoing links point outward.

Hierarchy and clustering are also investigated from the viewpoint of their backbone constructions (Article III). If two pre-existing concepts of A and B tie together as A→B, a new and third concept C can be built in terms of two pre-existing concepts, thus establishing a triangle pattern A → B → C ← A (Fig. 2). These structural patterns are meaningful (Bransford et al., 1999) and can also reflect the inductive or generative role of experiments (the experiments are explained in Chapter 2.3).

On the other hand, the backbone of hierarchy can be spoke-like. A pre-existing concept A can be linked to other extended concepts to facilitate the understanding of its examples and applications. This can occur through some branches of concepts such as {B, C, ...} (Fig. 2). These spoke-like patterns have the potential to mirror deductive or modeling procedures (models are illustrated in Chapter 2.3).

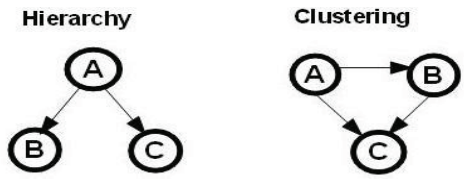

Figure 2 *Basic structural pattern of hierarchy with spoke-like structure on the left and basic pattern of clustering with triangular-cycle structure on the right (Note: directions are NOT coded here).*

A variety of other possible approaches or patterns could have been applied here, but many aspects of knowledge can already be captured by the patterns introduced above.

4 Teachers' representation forms

Teachers' pedagogical content knowledge (PCK) explains their knowledge of content as well as pedagogy. Shulman defined this notion for the first time in 1986. His theory introduced the interplay between teachers' content knowledge and pedagogical knowledge as a model which develops teachers' professional knowledge. In 1987, he argued that among the many categories that influence teachers' knowledge, a great deal of interest should be devoted to their PCK. "It (PCK) represents the blending of content and pedagogy into an understanding of how particular topics, problems, or issues are organized, represented, and adapted to the diverse interests and abilities of learners and presented for instruction" (p. 8). Thus, as mentioned in Chapter 2.1, this thesis explores the way teachers organize their SMK for their teaching purposes. From a similar perspective, teachers' ways of representing their knowledge are important and deserve more investigation. According to Abell (2007), because researchers have focused mainly on students' understanding, teachers' organization of knowledge has received less attention. A number of studies have investigated teachers' PCK and the most crucial categories that form or influence that knowledge (Tamir, 1988; Smith and Neale, 1989; Grossman, 1990; Marks, 1990; Cochran et al., 1993; Fernandez-Balba & Stiehl, 1995; Loughran et al., 2004; Hashweh, 2005; Park & Oliver, 2008; Rollnick et al., 2008). Park and Oliver (2008), for example, defined a "pentagon model" of PCK for teaching science. In their model, the teacher's understanding of PCK, instructional strategies for teaching science, assessment of science learning, orientation to teaching science and teacher efficiency form the corners of a pentagon. A review of most of the studies mentioned reveals that teachers' representation forms/strategies as a crucial part of teachers' PCK (Geddis & Wood, 1997) have seen little detailed study. We believe this is a noticeable gap in science teaching research because all accounts of PCK have clearly emphasized ReFs. "Within the category of pedagogical content knowledge, I include the most useful forms of representation of those ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations – in a word, the ways of representing and formulating the subject that make it comprehensible to others" (Shulman, 1986, p. 9). This thesis thoroughly explores the ReFs of teachers as a crucial part of their PCK (Articles II & IV), as well as the ReFs of university physics teachers (Article II) and upper secondary school teachers (Article IV). Further, Articles II and IV examine and discuss the interplay between the organization of knowledge, as an essential component of SMK, and ReFs, as a part of PCK. Our literature review shows that the relationship between teachers' organization of knowledge and ReFs thus far remains unexplored. We believe this bridge has the potential to cultivate teachers' professional knowledge and enhance their teaching and learning.

5 Research questions and research methodology

The focuses of this thesis are on the knowledge organization of teachers and textbooks on the one hand, and the ReFs of teachers' SMK on the other hand. We concentrated on the Biot-Savart law and Ampère's law as two central topics of magnetostatics at the university level as well as magnetic flux density and Ampère's law at the upper secondary school level. In order to examine these aspects explicitly, appropriate methods are employed.

5.1 Research questions

This research aims to answer the following questions:

1. How is knowledge of physics organized in teachers' SMK and the content of textbooks with regard to the Biot-Savart law/magnetic flux density and Ampère's law? What are the most shared concepts and structural patterns in the knowledge organization of teachers and textbooks?
2. Which representation forms do teachers use when teaching the Biot-Savart law/magnetic flux density and Ampère's law?
3. Can the organization of teachers' SMK be related to the representation forms they use?

The first question addresses the conceptual elements, the connections between them and, finally, their arrangements through teachers' SMK and the content of textbooks. This question reveals how different concepts, principles, and laws in physics tie together, and receives its answer in Articles I and III in the case of university textbooks, in Articles II and III in the case of university teachers, and in Article IV in the case of upper secondary school teachers. The organization of knowledge of teachers is compared to the textbooks which they use for their teaching purposes. Further, Article III examines and reports on the most important and shared concepts and structural patterns.

The second question addresses teachers' ReFs, which include a variety of models and experiments they use to translate their SMK. This question is investigated and its answer is given regarding university teachers (Article II) and upper secondary school teachers (Article IV). Article I investigates and answers the question of how the nature of links in textbooks represents the relationships between conceptual elements.

The third question refers to the correlation between teachers' organization of knowledge and ReFs as a whole. The answer to this question reveals how teachers' ways of arranging their SMK are related to the different ReFs they employ to convey their SMK (Article II). Furthermore, Article IV discusses the integration between the organization of knowledge which acts as a source of PCK and the organization which performs as a source of SMK.

Finally, the answers to these questions reveal the characteristics of the organization of teachers' SMK and the content of textbooks on the one hand, and the ReFs of teachers on the other.

5.2 Topics of this thesis: the laws of Biot-Savart and Ampère

In physics, these two topics are related to teaching how magnetic fields arise from electric current or electric current distribution (the equations appear in Table 1). However, in the "macroscopic phenomena to microscopic theories" approach (Guisasola et al., 2009), the Biot-Savart law [Eq. 1] can be used to calculate the magnetic field of any electric current distribution, while Ampère's law [Eq. 2] serves only for current distributions, which are highly symmetrical. The Biot-Savart law is explained in terms of either moving electric charges or current elements, which are the presumed sources of magnetic fields. According to some experiments and referring to the textbooks that are studied here, magnetic fields obey the superposition principle. It is therefore quite feasible to calculate the magnetic fields of any current distribution using the superposition principle and the Biot-Savart law. The most popular examples of magnetic fields that have been calculated from the Biot-Savart law include the magnetic fields of a long wire [Eq. 3], a current loop [Eq. 4], and a coil [Eq. 5]. Ampère's law describes the relationship between the circulation of a magnetic field around a closed loop and the flux of the electric current density along the surface bounded by the loop. Ampère's law, which is derived from the Biot-Savart law for the magnetic field of a long wire, can be employed for calculating highly symmetrical current distributions. The most common examples of symmetrical current distribution that can be calculated from Ampère's law include the magnetic field of a solenoid [Eq. 6], the magnetic field inside a wire [Eq. 7], and the magnetic field of a toroid [Eq. 8] (Guisasola et al., 2009). After students become acquainted with the laws of Biot-Savart and Ampère, they are expected to understand and illustrate the scientific explanations of a magnetic field due to the different configurations of moving charges, including all of the examples given above (e.g. long wire, solenoid) (Guisasola et al., 2009).

More advanced discussions involve other approaches such as "microscopic theories to macroscopic phenomena" to describe the Biot-Savart law and Ampère's law (Feynman et al., 1964). Current (moving charges) inside a wire generates a magnetic field, which is the departure point for theoretical arguments by Ampère. Then, by using Maxwell's equations (magnetic fields associated with steady currents) [Eq. 9] and applying Stokes' theorem [Eq. 10], we can "derive Ampère´s law" [Eq. 11]. Again, by using same parts of Maxwell's equations and applying vector potential [Eq. 12]; one can derive the Biot-Savart law either in terms of electric current density [Eq. 13] or electric current [Eq. 14]. To summarize, the context in this study is quite interesting because of the many ways one can approach the content as well as the many ways to organize its central concepts.

Table 1 *Formulas and equations for the Biot-Savart law and Ampère's law with details*

Equations	Details
Eq. 1 $\vec{B}_{\text{point charge}} = \frac{\mu_0}{4\pi}\frac{q\,\vec{v}\times\vec{r}}{r^2}$ $\vec{B}_{\text{current segment}} = \frac{\mu_0}{4\pi}\frac{I\,\Delta\vec{s}\times\vec{r}}{r^2}$	$\vec{B}$ (T) is magnetic field μ_0 is permeability constant; $\mu_0 = 4\pi\times10^{-7}$ Tm/A q (C) is charged particle $\vec{v}$ (m/s) is velocity r (m) is the distance from the charge θ defines as the angle between $\vec{v}$ and $\vec{r}$ I (A) is current Δs (m) is small length $\Delta\vec{s}$ is the vector (Knight, 2008)
Eq. 2 $\int \vec{B}\cdot d\vec{s} = \mu_0 I_{\text{through}}$	$I_{through}$ (A) is the current passes through an area bounded by a closed curve $\vec{B}$ (T) is magnetic field $d\vec{s}$ (m) small segment of length (Knight, 2008)
Eq. 3 $B = \frac{\mu_0}{2\pi}\frac{I}{d}$	I (A) is current d (m) is the distance between the point identified to calculate the magnetic field and wire (Knight, 2008)
Eq. 4 $B_{loop} = \frac{\mu_0}{2\pi}\frac{IR^2}{(z^2+R^2)^{3/2}}$	R (m) is the radius of the loop z (m) is the distance between the point identified to calculate the magnetic field and centre of loop (Knight, 2008)
Eq. 5 $B_{centre\ of\ coil} = \frac{\mu_0}{2}\frac{NI}{R}$	R (m) is the radius of the coil N is total number of turns (Knight, 2008)
Eq. 6 $B_{solenoid} = \frac{\mu_0 NI}{l} = \mu_0 nI$	l (m) is width of the integration path $n = \frac{N}{l}$ (1/m) number of turns per unit length (Knight, 2008)
Eq. 7 $B_{inside\ wire} = \frac{\mu_0 I}{2\pi R^2} r$	R (m) is the radius of the wire r (m) is the distance from the centre r<R of wire (Knight, 2008)
Eq. 8 $B_{toroid} = \frac{\mu_0 IN}{2\pi}\frac{1}{r}$	r (m) is the radius of the concentric circle N is total numbers of turns (Halliday et al., 2007)
Eq. 9 From Maxwell $\Delta\cdot B = 0$ $c^2\nabla\times B = \frac{j}{\varepsilon_0}$	B (T) is magnetic field c (m/s) is speed of light j (A/m^2) is electric current density ε_0 is permittivity constant; $\varepsilon_0 = 8.85\times10^{-12}$ (C^2/Nm^2) (Feynman et al., 1964)
Eq. 10 $\int_\Gamma B.ds = \int_s \nabla\times B\cdot n ds$	The integral around any closed path (Γ) of any vector field is equal to the surface integral (s) of the normal component of the curl of the vector. (Feynman et al., 1964)

Eq. 11 $\oint_{\Gamma} B \cdot ds = \frac{I_{through\ \Gamma}}{\varepsilon_0 c^2}$	$I_{through}$ (A) is current through the loop Γ The circulation of B around any closed curve is equal to the current I through the loop, divided by $\varepsilon_0 c^2$ (Feynman et al., 1964)
Eq. 12 $A(1) = \frac{1}{4\pi\varepsilon_0} \int \frac{j(2) dV2}{r_{12}}$	$A(1)$ (v) is vector potential at point 1 $j(2)$ (A/m^2) is electric current density at point 2 $dV2$ (m^3) is the small volume segment at point 2 r_{12} (m) is the distance between A(1) and j(2) dV(2) The vector potential A at point 1 is given by an integral over the current elements j dV at all points 2 (Feynman et al., 1964)
Eq. 13 $B(1) = \frac{1}{4\pi\varepsilon_0 c^2} \int \frac{j(2) \times e_{12}}{r_{12}^2} dV2$	B(1) (T) is the magnetic field at point 1 e_{12} is the unit vector in the direction to A(1) from j(2) dV(2) (Feynman et al., 1964)
Eq. 14 $B(1) = -\frac{1}{4\pi\varepsilon_0 c^2} \int \frac{I e_{12} \times ds_2}{r_{12}^2}$	ds_2 (m) is element of length of wire at point 2 j dv in Eq. 13 is replaced by I ds in Eq. 14 (Feynman et al., 1964)

5.2.1 Motivations behind these topics

The motivation for studying the laws of Biot-Savart and Ampère stems from the dominant theories of electricity and magnetism, which play an important role in students developing an understanding of field theory. From a historical perspective, one must consider the pioneering position of electromagnetism; even nowadays, the differential magnetic field of current elements is the starting point for calculating the magnetic field generated by any steady electric current (Erlichson, 1998). These topics were selected for investigation as they promise to reveal differentiating dispositions in the organization of knowledge of university physics teachers and textbooks. The laws permit two inverted approaches of such organization: "empirical results first" and "theory second" or vice versa, which can presumably be traced back to teachers' organization of their SMK. These laws can shed light on the different roles of field concepts, different formulations for how the theoretical model is related to the basic entities, and finally, different models through which the laws are illustrated.

4.2.2 Students' misconceptions and difficulties with these topics

Studies of magnetism and electromagnetism have revealed the following often repeated student misconceptions and difficulties: confusion between electric charges at rest and moving charges as sources of a magnetic field, struggling to understand how a magnet can generate a magnetic field, problems in understanding the relationship between a spiral of current and recognizing the virtual existence of magnetic field lines, conflating magnetic field with magnetic force, problems with the effects of a magnetic field on charges at rest, difficulties finding out the vectorial relationship between field and force, and finally, students' tend to focus on the formula and equations rather than on the meaning of the concepts (Guisasola et al., 2004; 2009). Concerning Ampère's law, Manogue et al. (2006) found that students often experience difficulty understanding the following aspects: steady current and current density; the distinctions between line, surface, and volume densities; and that total current is a flux. In addition, students appear unable to cope with the behaviour of a magnetic field in a special geometric. These instances raise the cognitive load of understanding Ampère's law.

Although the current study does not address issues directly related to students' learning of magnetostatics (e.g. Saarelainen et al, 2007), one can still see that recognizing the meaningful structural patterns and organizations of core concepts of magnetostatics with a focus on the laws studied here can reduce the aforementioned confusions and difficulties (Bransford et al., 1999).

5.3 Research methodology

This thesis employed questionnaires, interviews, and concept maps as research tools to investigate 1) the organization of knowledge of university and upper secondary school teachers and well as of university textbooks, and 2) teachers' ReFs.

5.3.1 Teachers and textbooks in this study

The textbooks that the participating teachers employed for their teaching purposes were the Fundamentals of Physics (referred to hereafter as FP) (Walker et al., 2008) and Physics for Scientists and Engineers (referred to hereafter as PSE) (Knight, 2008). These are two standard introductory physics textbooks for physics education at universities throughout the world. Teachers at the University of Helsinki's department of physics also refer to these books when designing their teaching instructions and plans. The teachers involved in this study are representative of instructors of introductory physics courses at the Department of Physics. All of them have earned their PhD degrees in Finland and hold the position of Docent (Adjunct professors) at the University of Helsinki. In line with university policy, about 30% of their working hours are spent on teaching responsibilities. Two of these teachers specialize in accelerator and material physics (John and Nigel). One teacher focuses on material and nanoscience as well as X-ray physics and soft condensed matter (David). The fourth teacher works in the two fields of material physics and science education (Chris). By virtue of their research, the participants are presumed to be familiar with the topics of the Biot-Savart law and Ampère's law, as these are fundamental in their fields. Moreover, all of the teachers teach these topics to their introductory physics students in the context of magnetostatics, which each of the teachers has taught for at least five semesters.

As reported in Article IV, two upper secondary school teachers participated in our study. Both teachers teach physics in upper secondary schools in Helsinki and are contributing authors of two different high school physics textbooks in Finnish. One teacher had completed a minor in computer science and teaches in an international program in a Finnish high school. He is a native English speaker, but graduated in Finland and has 11 years of teaching experience in Finland. The other teacher is a native Finnish speaker who has taught at a Finnish high school for more than 20 years.

Given their years of teaching experience, all of the participating teachers can be considered experts. According to Hashweh (2005), who argued that "teachers' pedagogical construction develops through experience", investigations of the organization of knowledge and ReFs of these teachers can shed light on the relationship between PCK and SMK.

5.3.2 Questionnaires and concept maps in university textbooks

The first step in studying the organization of knowledge was to identify the conceptual elements through the content of three university textbooks (Knight, 2008; Feynman et al., 1964; Walker et al., 2008) on the laws of Biot-Savart and Ampère (Article I). Next, we studied the ways these elements were linked. For this reason, we identified the natures of the links and, through some qualitative interpretative analysis, established a categorization of links. We validated this categorization of links with questionnaires. Six questionnaires inquired about two topics and three textbooks. Four university lecturers at the University of Helsinki, Department of Physics participated in these questionnaires. We examined the levels of agreement between the lecturers and the established categorization of links with five Likert scale questionnaires. The results revealed that participating teachers agreed with 75% to 80% of the proposed categorizations, which reflects a high level of agreement. Thus, we applied conceptual elements and links to visualize the knowledge organization via concept maps. The structural characteristics of the content of the textbooks were evaluated by a hierarchy and interactive processes within their concept maps, as proposed by Kinchin et al. (2000) and Hay et al. (2008) (see Chapter 3).

5.3.3 University teachers' interviews and concept maps

In the second stage (Article II), we studied the organization of the university teachers' SMK (the teachers from the previous stage of research). However, the interviews took place one year later, so the period gap between the interviews and the questionnaires masks the relative influences of the knowledge arrangements of the textbooks on the teachers, thus assuring the reliability of the study. Before interviewing the teachers, the author of this thesis provided several concepts from the content of the three textbooks studied. These concepts varied from the sources of a magnetic field to typical concepts relating to the laws of Biot-Savart and Ampère, electrostatic concepts, and advanced concepts in magnetostatics. All these concepts were written on concept cards which could be pasted onto a white board provided in the interview room. The author of this thesis, who was also the interviewer, instructed the teachers in advance about the use and application of concept maps. The teachers were asked to select from those concepts and were allowed to add concepts where they deemed it necessary. They placed the concepts into an order that they planned on following when teaching the Biot-Savart law and Ampère’s law. They selected the concepts, drew lines between them, and explained or justified the relationships between the concepts (Mile & Huberman, 1996). At the end of the interviews, a concept map belonging to the teachers remained on the white board. The way the teachers organized the concepts functions as their SMK, and their explanations serve as their forms of representation, which addresses their PCK. The teachers’ organization of SMK was investigated through the concept maps they constructed. On the other hand, the categories related to representational forms were identified through the transcripts of their interviews. The author of this thesis and her colleague identified these categories and triangulated the results. Content analysis of the interview data revealed four main domains: 1) Introduction to the Biot-Savart law, 2) Application of the Biot-Savart law, 3) Introduction to Ampère’s law, and 4) Application of Ampère’s law. These domains were chosen based on Oser and Baeriswyl (2001), who stated that the introduction and application of new concepts are essential categories for knowledge forming and concept building. Introductions address the definitions of new concepts, whereas applications refer to examples and implications of already-defined laws. The organization of knowledge and ReFs of teachers were examined in conjunction with these four domains (Articles II & III). Knowledge organization of teachers was studied using several dead-ended concepts as well as loops and cycles in their concept maps, which we explain in Chapter 2.3. The categories of teachers’ ReFs emerged from the content analysis of the interviews. They evolved mainly around models and experiments, and their frequencies were reported, as explained in Chapter 3.

5.3.4 Comparing the knowledge-ordering patterns of university teachers and textbooks

The third stage of this study used a comparison method to compare the knowledge organization of university physics teachers and the textbooks they use for their teaching purposes on the topic of the Biot-Savart law and Ampère’s law. For comparison, four concept maps produced by teachers (Article II) were compared to two concept maps of the textbooks studied (Article I). Our survey showed that these teachers used textbooks for their teaching purposes, so the choice of textbooks was neither optional nor arbitrary. Here, an in-depth analysis of the structural properties of maps revealed how the organization of the teachers’ knowledge was compared to the arrangements presented in the textbooks (Article III). Comparisons of the structural patterns of the teachers and the textbooks from the viewpoints of clustering and hierarchy revealed information about the knowledge ordering and can provide a foundation for quantitative comparisons. This method apparently connects to the way in which knowledge is introduced in teachers’ teaching and in the content of textbooks, which can be deductive or inductive.

5.3.5 Upper secondary school teachers studies: questionnaires, observation of lessons, concept maps

The last stage of this thesis uses questionnaires, concept maps, and classroom observations to investigate upper secondary school teachers' organization of knowledge and the representation forms they use. We contacted and invited 89 Finnish high school physics teachers to participate in our online questionnaires, which were in electronic format and contained questions about the teachers' background, the organization of magnetic flux density and Ampère's law, as well as the teachers' representation forms for teaching these topics. The questionnaires contained both Likert scale and open-ended questions. We utilized thirteen concepts of magnetostatics from a well-known Finnish textbook to present to the surveyed teachers. The teachers were asked to prioritize these concepts according their points of view. Furthermore, teachers had an opportunity to construct their concept maps, because we provided them with an environment in which to build them. The environment created with the Cmap Tool (Florida Institute for Human & Machine Cognition (IHMC)) and attached as a supplement to the online questionnaire, contained the same 13 concepts without sketches of the relations or links between them. Teachers were at liberty to construct concept maps, which were compared to those presented in the same textbook from which the 13 concepts were extracted. Concept maps were analysed from the viewpoints of the core concepts and incoming and outgoing links (see Chapter 3). Consequently, triangulating different methodologies, such as that utilized here, provides more insight into teachers' SMK and PCK as a whole (Baxter & Lederman, 1999).

Questions regarding ReFs addressed the frequency and importance that teachers attribute to different models, experiments, explanations, and descriptions. The rest of the questions belonged to students' misconceptions or difficulties about learning or understanding magnetic flux density or Ampère's law. We received a total of six answers from the invited teachers (6.74%), so we decided to qualitatively analyse the answers by investigating open-ended questions. Since only two of the six teachers provided us with information, we decided to perform case studies. We then collected additional data and extended our analysis of teachers by videotaping lessons of one teacher and analysing the concept maps of the other teacher mentioned.

6 Results

The results of this study appear in Articles I-IV and are summarized below. First, Chapter 6.1 briefly illustrates examples of the teachers' concept maps and textbooks. Second, Chapter 6.2 summarizes and reports the findings regarding the teachers' organization of SMK and textbooks as well as their structural patterns and properties for topics of the Biot-Savart law and Ampere's law (Articles I-IV). Next, representation forms as a part of PCK, which teachers employ to translate their SMK, are reported in Articles (II, IV) and summarized in chapter 6.3. Finally, the relations and interplay between the organization of teachers' SMK and their ReFs as a crucial part of PCK are examined and discussed in Articles II and IV, and then these are summarized in chapter 6.4.

6.1 Examples of the concept maps of teachers and textbooks

In the case of university teachers' concept maps, we express the structural properties discussed in Articles II and III. With regard to the concept maps of university textbooks, we briefly illustrate the structural characteristics considered in Article I. For the upper secondary school teachers' concept maps, the organization of knowledge and its features are discussed in Article IV. Articles I, II, and III do NOT take into account the direction of links, and none of the articles in this study stresses the weight of links. All university teachers' interviews and university textbook presentations (Articles I, II, III) were analysed in the same way. Next, a summary of all analyses in the form of similar types of domain-specific representations appears in Articles II and III in order to enable the comparison of knowledge organization patterns, which is a novel part of this study.

6.1.1 Example of the concept maps of a university teacher

Teachers' concept maps are taken directly from the interviews. The nature of the links (e.g. models and experiments) is added after parallel analyses of the videotaped interviews (explained in Chapter 5.3.3). Fig 3 below presents a sample of teachers' concept maps and the way they organize their SMK.

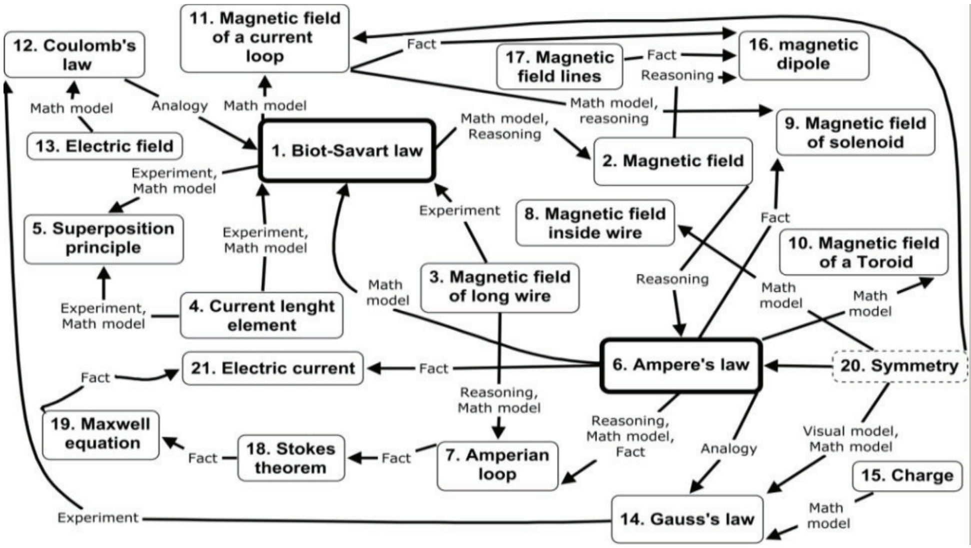

Figure 3 *A sample of teachers' concept maps visualizing the organization of their SMK of the laws of Biot-Savart and Ampère. Numbering of the concepts follows the order in which the teacher introduced the concepts in the interview. The nature of links (propositions) has been added after parallel analysis of the interviews (David in Articles II & III).*

As Fig 3 shows, the teacher's concept maps include some **loops and cycles,** which reveal its connectivity, as well as some **dead-ended** concepts, which make the connectivity of the structure fragile (see the results of Article II). For instance, Ampère's law (6 in Fig 3) is an analogy for Gauss's law (14), so they are connected via a link. Symmetry (20) serves as a mathematical and visual model to describe Ampère's law, so they are also tied together. Symmetry is also connected to Gauss's law, as it is to its analogous law. The link between 20 and 14 is an example of a cross-link which generates a loop of 20 → 6 → 14 ← 20. Further, the concepts of a magnetic field inside a wire (8), the magnetic field of a toroid (10), an electric field (13), a charge (15), and magnetic field lines (17) are disconnected from the rest of the map. Such concepts reduce the connectivity and coherency of the whole structure and are considered dead-ended concepts. Although this map covers six meaningful cycles within four introduced domains (see Chapter 5.3.3), it incorporates five dead-ended concepts within its structure (see Table 3 in Article II). Consequently, from the view point of the connectivity of organization, this map falls into the category of a moderately connected structure (Article II).

According to Fig 3, David's concept map exhibits **triangles** and **spokes** (see the results of Article III). The triangles indicate the interwoven structure that results from certain concepts. Triangles (e.g. 4 → 1 → 5 ← 4) show how the existence of two already-defined concepts (4 → 1: current length elements → Biot-Savart) can be applied to explain the relationship to the third concept (4 → 5: current length element → Superposition & 1 → 5: Biot-Savart → Superposition). Thus, meaningful relationships between the three concepts can be visualized as triangles. Triangles can reflect inductive-like structures, such as the generative properties between the Biot-Savart law, the current length element, and superposition principles. Branches or spokes can serve to indicate how a core concept is connected to its siblings (e.g. 1 → {2, 3}: Biot-Savart law → {magnetic field, magnetic field of a wire}). Often, a core concept is linked to its applications or implications via spoke-like structures. As noted earlier, branches represent the hierarchical levels as well as the deductive-like structure of knowledge. In Articles II and III, results are reported regarding four related domains, as mentioned in Chapter 5.3.3. These domains are introductions and applications of the Biot-Savart law which follow Oser and Baeriswyl's (2001) suggestion regarding knowledge formation and concept building.

6.1.2 Example of the concept maps of a university textbook

An example of a constructed concept map of the textbook of Knight (2008) appears in Fig 4. The maps representing the knowledge organization in the textbooks are the author's interpretations, based on the same rules for constructing the maps as those used for the teacher interviews.

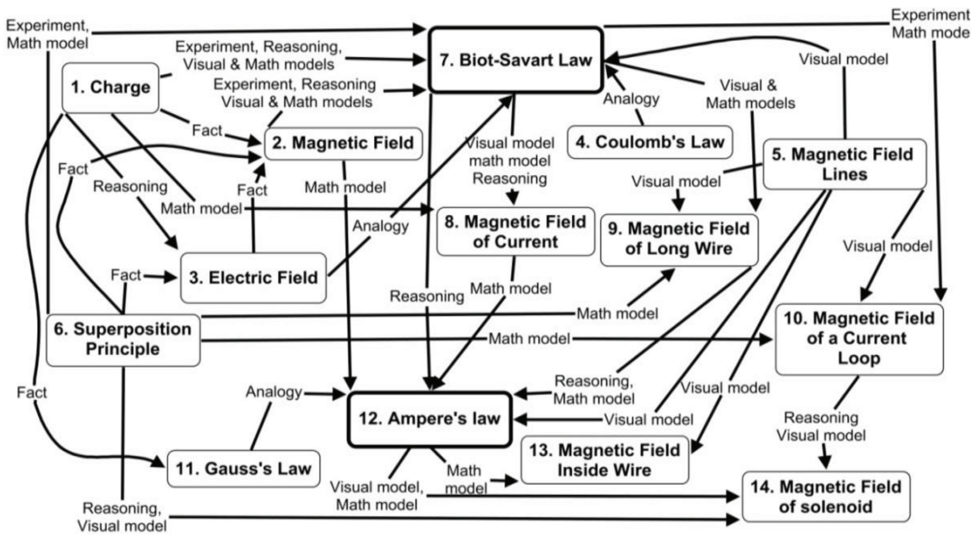

Figure 4 *Concept map of the textbooks of Knight (2008) as an example of the organization of the laws of Biot-Savart and Ampère (numbering of the concepts reflects in the order in which they are introduced in Knight, PSE in Articles I & III).*

The structure of the textbook's concept map, which appears in Fig 4, displays an interconnected arrangement. The different concepts in this map share many **cross-links** as well as many **incoming and outgoing** links. For example, according to the textbook's content, the Biot-Savart law (7 in Fig 4) is connected to the magnetic field of a current (8) via a visual model, a mathematical model, and reasoning. On the other hand, charge (1) is connected to the Biot-Savart law by means of experiments and other models mentioned above. In line, a charge is tied to the magnetic field of a current by a mathematical model which is presumably a cross-link. This map contains other such cross-links which expose the **interconnectivity** of the structure. Therefore, knowledge organization is considered an interactive process. This organization also contains many justifiable levels, which shows a good level of **hierarchy**.

6.1.3 Example of the concept maps of an upper secondary teacher

Part of the concept map of an upper secondary school teacher who participated in our study appears below (Article IV). His concept map is more comparable to traditional maps where the teacher uses propositions, including verbs.

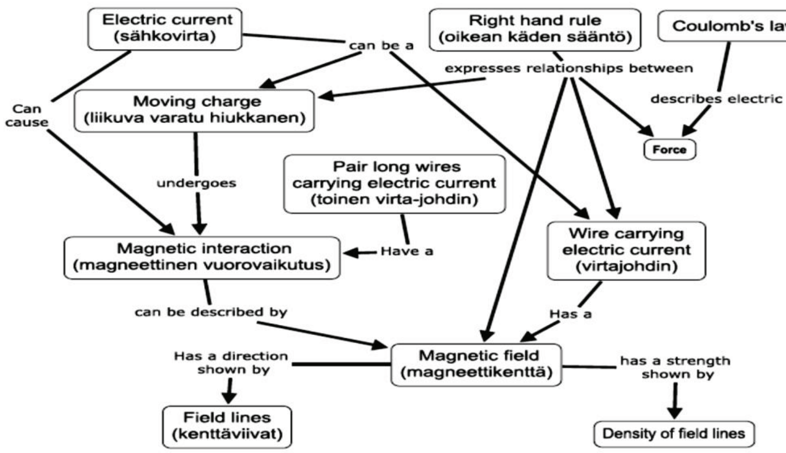

Figure 5 *Part of the concept map of an upper secondary school teacher. The map shows how the teacher arranged his subject matter knowledge regarding magnetic flux density (Article IV).*

In this part, we emphasize **core concepts** as well as **outgoing** and **incoming** links. One of the cores, most central concepts in this map, is the magnetic field, which has five attached links. As Fig 5 shows, three of those links are incoming and two are outgoing. For example, the teacher stated that magnetic interaction “can be described by” a magnetic field or that a magnetic field “has a direction shown by” field lines. The details of the analysis of the teacher’s concept maps appear in Article IV. As an indication of the paralleled organization of knowledge, the teacher’s map is compared to a standard upper secondary school textbook (see Chapter 6.2.4).

6.2 Organization of the subject matter knowledge of teachers and and textbooks

It is of interest to study the knowledge organization of physics teachers and textbooks in university and upper secondary schools as "a largely unmapped field of study" (Abell, 2007; p. 1117). Their organization of knowledge were studied by means of concept maps in Articles (I-IV). Further, some of the prioritized concepts used by upper secondary school teachers were recognized from their responses to questionnaires (Article IV).

6.2.1 Organization of the subject matter knowledge of university physics teachers

The SMK of teachers is examined with a focus on the ways in which they order and arrange their knowledge. The summary of the results indicated that teachers' knowledge organization was strongly connected to the topic of the Biot-Savart law, while their knowledge was moderately bounded by the topic of Ampère's law (Article II). As mentioned in Chapter 1, three classes of the organization of knowledge were emerged from an analysis of four university teachers' concept maps:

Strongly connected includes many loops and cycles with no dead-ended concepts. The **moderately** connected class contains fewer loops than the strongly connected class and has few dead-ended concepts. The **loosely** connected class has limited numbers of loops and includes many dead-ended concepts.

Table 2 summarizes the information about the number of loops and dead-ended concepts through the knowledge organization of one of the teachers interviewed. As noted earlier, university teachers' organization of knowledge and ReFs are described in terms of four related domains. Next, we discuss which classes of the organization of knowledge best fits this teacher. The concept map of this teacher appears in Chapter 6.1.1.

Table 2 *Structural patterns of each domain in the concept map of an interviewed university teacher (David) with an emphasis on loops and dead-ended concepts (Article II). The numbers refer to Fig 3.*

Domains	Dead-ended concepts	Loops and cycles	Connectedness of knowledge organization
First domain: Introduction to Biot-Savart law	-	(1→5→4→1)	Strongly connected
Second domain: Applications of Biot-Savart law	13, 17	-	Moderately connected
Third domain: Introduction to Ampère's law	-	(11→16→2→1→11)	Strongly connected
Last domain: Applications of Ampère's law	8, 10, 15	(21→6→7→18→19→21); (20→6→14→20); (6→9→11→20→6)	Moderately connected

As Table 2 indicates, this teacher's knowledge organization varied from a moderately connected to a strongly connected structure. Thus, we can assume that this teacher's knowledge organization is moderately connected as a whole.

6.2.2 Organization of the subject matter knowledge of university physics textbooks

Article I depicted through concept maps and discusses the results regarding the knowledge organization of three university textbooks (Feynman et al., 1964; Walker et al., 2008; Knight, 2008) on two topics of magnetostatics. Their knowledge organization is investigated by focusing on two domains of the Biot-Savart law and Ampère's law. The structures of the concept maps are studied in terms of disconnected concepts as well as incoming and outgoing links to core concepts (see Chapter 3).

Although the results indicate that these three textbooks contain similar conceptual elements, they nevertheless differ from each other: the textbook written by Feynman and colleagues used more advanced conceptual elements within the content of textbook. The content of other two textbooks employed more applications and implications of the concepts (see Table 1 in Article I). The density of the links in the textbook of Feynman et al. was less than that of the other textbooks. When examining the connections/links between concepts in the concept maps, Feynman et al. connect the links mainly to core concepts. Nevertheless, the other two textbooks, share many cross-links between the other concepts rather than links between only core concepts and other concepts. The structural properties of all three textbooks were evaluated with respect to hierarchy and interactive processes (Kinchin et al., 2000; Hay et al., 2008). The structure of Feynman's textbook shows limited hierarchical and justifiable levels, most of its links are "incoming" links to core concepts (the laws of Biot-Savart and Ampère), and its arrangement includes many disjointed concepts (Fig 2 in Article I). The organization of knowledge of the textbooks of Knight (2008) and Walker et al. (2008), contains both incoming and outgoing links; besides, they embrace only a few unconnected concepts (Figs 3 & 4 in Article I). Conclusively, the knowledge organization of Feynman's textbook reflects a simple structure, whereas the other textbooks show more flexible and interconnected structures.

6.2.3 Comparison of the organization of university physics teachers and the textbooks they use for their teaching purposes

Article III complements the study of the organization of knowledge in university textbooks and lecturers with regard to the laws of Biot-Savart and Ampère. The teachers and textbooks are same as those in Articles I and II. Along with an earlier study in Article II, the organization of knowledge of teachers and textbooks was compared to four domains of introductions and applications of the laws of Biot-Savart and Ampère. We evaluated structural properties focusing on clustering and hierarchy. Clustering describes the connectivity between conceptual elements, whereas hierarchy describes the degree of top-down ordering (overarching hierarchy) in knowledge organization. The results indicate that clustering in the first two domains (for the Biot-Savart law) is higher than in the other two domains (for Ampère's law). The hierarchy in domains 1 and 2 remains lower than in 3 and 4. The clustering behaves similarly for the case of patterns between textbooks and teachers in all domains except the last one (Tables 2-5 in Article III). This indicates that while given domains have their individual differences, the role of inductive-like patterns and the triangular patterns related to them are used more extensively in domains 1, 2, and 3 than in domain 4. This indicates that experimental background provides greater justification in former domains than in the latter domain. This is supported by the fact that the hierarchy is a considerably more pronounced feature of patterns in domains 3 and 4 than in domains 1 and 2. This shows that the structural patterns of the topic of Ampère's law are more deductive-like than inductive-like. The next important conclusions indicate that the hierarchical organization between the knowledge of teachers and textbooks varies from one topic to another. The hierarchical organization of teachers is more comparable to that of textbooks for the topic of the Biot-Savart law. As an example, Fig 6 depicts knowledge organization patterns used by one teacher and one textbook for domains 1 (Introduction to the Biot-Savart law) and 3 (Introduction to Ampère's law). Next, the structural measures of knowledge of this teacher and textbook appear in Table 3.

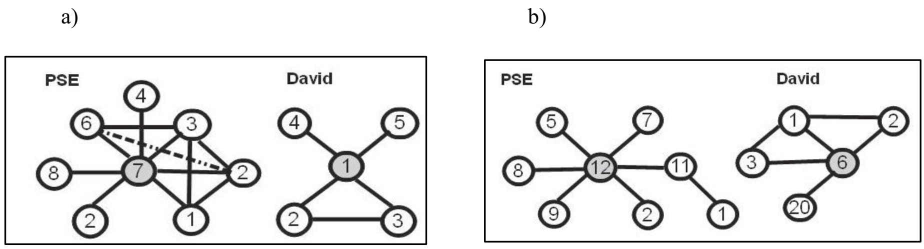

Figure 6 *Examples of the knowledge organization patterns used by a teacher (David) and a textbook (PSE) for a) Introduction to the Biot-Savart law (domain 1 in Fig 6a) and b) Introduction to Ampère's law (domain 3 in Fig 6b). The numbering refers to the concepts maps in Figs 3 & 4.*

One should bear in mind that Fig 6 and Table 3 show the individual differences between only one teacher (David) and one textbook (PSE). Therefore, some of conclusions made above should be considered carefully.

The domain-specific patterns of knowledge organization in Fig 6 show that for David, patterns seem rather economical, and relatively few concepts are utilized in justifying the central concepts (1 in Fig 6a refers to the Biot-Savart law). The patterns representing the knowledge organization of PSE is more complex and contains more concepts (7 in Fig 6a refers to the Biot-Savart law).

From the organization patterns in Fig 6b, one can notice that David's knowledge organization seems more connected than that of PSE. These organizations are deemed characteristic of cases where inductive or generative experiments are central. Structural patterns of PSE in Fig 6b show the extensiveness of its content where deductive-like structures are central. These differences can be quantified more precisely in terms of clustering and hierarchy, as Table 3 summarizes below. To see how the values of clustering and hierarchy are obtained, see the Appendix in Article III.

Table 3 *Structural measures of the knowledge of a teacher (David) and a textbook (PSE) for domains of the Introduction to the Biot-Savart law and Ampère's law.*

Structural measures	**Introduction to the Biot-Savart law For PSE**	**Introduction to the Biot-Savart law For David**	**Introduction to Ampère's law For PSE**	**Introduction to Ampère's law For David**
Total number of links	11	5	7	6
Number of spokes	1	1	15	-
Hierarchy measure	0.1	0.2	2.14*	
Number of triangles	5	1	-	2
Clustering measure	0.45	0.2		0.33

Hierarchy = Number of spokes, including either the Biot-Savart law or Ampère's law/Total number of links; Clustering = Number of triangles that contain either the Biot-Savart law or Ampère's law/Total number of links * H >> 1 shows a very sophisticated hierarchy

As Table 3 shows, the knowledge organization of PSE consists of many links revealing the richness of content. The hierarchy (related to the number of spokes) is larger in David's case for the Introduction to the Biot-Savart law. This is most probably connected to the use of the deductive-like introduction of new knowledge. In this domain, the hierarchy in David's structural patterns is incomparable to that of PSE, since the hierarchy in David's knowledge for the Introduction to the Biot-Savart law is two times more than that of PSE (results in Article III). The clustering measures are higher for PSE, indicating a strong tendency toward locally tight connections between conceptual elements (domain 1: the Introduction to the Biot-Savart law). This could reflect the inductive-like or generative properties related to knowledge ordering. Again, clustering in David's structural patterns is approximately half that of PSE.

The knowledge structure of PSE regarding the Introduction to Ampère's law (domain 3) has many spoke-like structures revealing the sophisticated hierarchy (H >> 1, cf. Koponen & Pehkonen, 2010) and the existence of a deductive type of modeling in their organizations. Nevertheless, David's organizational patterns look more connected, thereby mirroring the inductive type of structures. The clustering evident in David's structural patterns is incomparable to that in PSE, which in this domain is zero.

Although other teachers shared some triangles or spokes with textbooks, such was not the case for David and PSE (see results in Article III). Once again, only triangles and spokes containing either the Biot-Savart law or Ampère's law are coded here. In this study, loops, which include more than three concepts, are not considered clusters for two main reasons: first establishing an inductive and generative basis by having loops that include more than three concepts is more difficult; second, the number of triangles defines the clustering (da Costa et al. 2007), so the focus falls on triangular connections.

6.2.4 Organization of the subject matter knowledge of upper secondary school physics teachers

Article IV investigates the conceptualization of the knowledge organization of upper secondary school teachers regarding magnetic flux density and Ampère's law by means of two case studies. Responses to the questions about the organization of knowledge showed that for some of the prioritized concepts, the organization of knowledge was consistent between the teachers. Disagreements over ordering in singular instances (magnetic flux density, magnetic density, moving charge, Ampère's law) could be attributed to their individual teaching approaches (Phenomenological versus Formulaic). One teacher represented his organization of knowledge through a concept map that illustrated his mental conceptions regarding magnetostatics. His map includes two not immediately meaningful domains. Investigations of the first domain of his map showed that magnetic field, magnetic interaction, and the right hand rule were the core concepts in his map (see Fig 5 in Chapter 6.1.3). Analysis of the next domain showed that concepts of coil and magnetic field were central (Fig 1 in Article IV). The concept maps from the high school physics textbooks (Hatakka et al., 2008) were compared to the teacher's map as an indication of the parallel organization of knowledge in magnetostatics. This enables us to determine the main differences between the organization of knowledge in the SMK of teachers and textbooks (Article IV, p. 75-76). For example, the concept map of the textbook shows that the right hand rule is imagined as neither incoming nor outgoing links from the magnetic field. In a different perspective, the right hand rule in the teacher's concept map is directly linked to the magnetic field as an incoming link (Table 4 in Article IV). Conclusively, differences between the teacher's organization of knowledge and the textbook's concept map for describing magnetic flux density reveal the difficulty of distinguishing between magnetic field and magnetic interaction. Although we detected differences between incoming and outgoing links, more similarities between the organization of knowledge of teachers and textbooks for explaining magnetic fields have been recognized in comparison to magnetic interaction.

6.3 Representation forms used by teachers

It is of interest to investigate different forms of representation which teachers utilize to transform their SMK. This recognized as an important component of teachers' PCK (Shulman, 1986; 1987). ReFs of used by university teachers for teaching laws of Biot-Savart and Ampère are studied by means of parallel analysis of interviews in Article II. On the other hand, ReFs of upper secondary school teachers are investigated in Article IV through online questionnaires and analysis of classroom observation regarding magnetic flux density and Ampère's law.

6.3.1 Representation forms of Biot-Savart law and Ampère's law used by university teachers

ReFs used by university teachers are identified from the content analysis of interviews. These consist of seven categories as follows:

Descriptive and explanatory mathematical models connect conceptual elements through mathematical relations or equations. However, a descriptive model is applied to define new laws or concepts, while an explanatory one explains the applications or examples of already-defined laws. A **visual model** is about visual perceptions, which use figures and diagrams to help one visualize different conceptual elements. A **statement of fact** concerns declarative knowledge and describes a given set of facts. An **experiment** provides information about an observation, discoveries, and phenomena. **Reasoning** is a mode of presentation which can be considered a model that provides reasons or arguments to justify the connections between conceptual elements. **Analogy** is seen from the perspective of mapping between similar conceptual elements.

The frequencies of use of the categories of ReFs by university teachers mentioned above were measured with respect to four domains of the introduction and application of Biot-Savart's law and Ampère's law and appear in Table 4 below.

Table 4 *The different domains and frequencies of use of representation forms in each domain (the numbers of cases appear in parentheses) (Article II)*

Categories	Introduction to Biot-Savart law (N = 20)	Applications of Biot-Savart law (N = 11)	Introduction to Ampère's law (N = 20)	Application of Ampère's law (N = 17)
Experiment	3	-	1	2
Analogy	1	3	1	4
Des- math model*	**6**	-	4	4
Exp- math model*	3	**7**	1	**6**
Statement of fact	3	-	4	1
Visual model	-	1	3	-
Reasoning	4	-	**6**	-

*Des = descriptive; Exp = explanatory

Analysis of the ReFs in the first domain indicated that these forms were evenly distributed (Table 4). The most applied form for introducing the Biot-Savart law was the descriptive mathematical model (30%), but no visual model was used in this domain. In the second domain, ReFs were not evenly distributed, but were instead accumulated by the explanatory mathematical model (63%). Experiment, the descriptive mathematical model, the statement of fact, and reasoning were absent from this domain. The ReFs that teachers used to introduce Ampère's law (the third domain) were somehow evenly distributed. The leading form in this domain was reasoning (30%), but experiment, analogy, and explanatory math models saw little use in this domain. The overall view of the last domain shows that ReFs were not uniformly distributed there. The most crucial form was the explanatory mathematical model (35%), while the visual model and reasoning were not employed in the last domain.

6.3.2 Representation forms of magnetic flux density and Ampère's law used by upper secondary school teachers

Information about ReFs for upper secondary school physics teachers comes from two teachers' responses to online questionnaires. Details of this information appear in Table 5 of Article IV. For instance, one teacher stated that "A wire swinging in a vertical magnetic field is an example or application of magnetic field density." The other teacher posited that "Qualitative experiments which do not have the mathematics yet are the most appropriate experiments for Ampère's law." In addition to responses to questionnaires, the observation of lessons provided more insight into the investigation of ReFs. Some selected instances appear in Article IV (p. 79-80), which we can read from the teacher's use of ReFs, the way he taught the topics of magnetic flux density for moving charges, magnetic flux density for current-carrying wires, and Ampère's law. Analysis of the videotaped lessons and responses to the questionnaires suggested improved better way to approach ReFs. We therefore identified some categories which are open to refinements and extensions. We considered these categories to be describable -at least two dimensionally- in terms of the character of discourse and the medium of instruction (Fig 6 in Article IV).

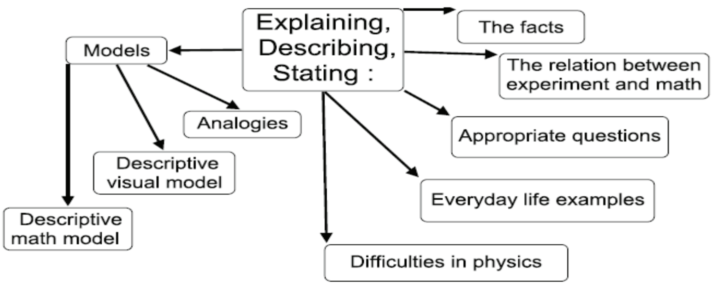

Figure 7 *Recognized categories of teachers' representation forms (ReFs) from questionnaires and observed lessons.*

The first dimension, "character of discourse", appears in the big box in Fig 7, along with the second dimension, "medium of instruction". These categories were inspired by the ReFs of university teachers discussed in the previous Chapter (6.3.1) and Article II. Moreover, these categories are in line with the arguments of Shulman (1986), Geddis and Wood (1997), Loughran et al. (2004), and Hashweh (2005), who stated that ReFs include analogies, illustrations, examples, explanations, and simulations.

6.3.3 Caregories of links in university textbooks

In examining how conceptual elements in the knowledge of physics in textbooks were connected, we categorized the links between the concepts as discussed in Chapter 2.3. These categories are concurrent with categories of the ReFs of university teachers and include **descriptive** (DM in Fig 7) and **explanatory mathematical models** (EM in Fig 7), a **visual model** (VM in Fig 7), a **statement of fact** (SF in Fig 7), **reasoning** (R in Fig 7), and a **reference to previous knowledge** (RPK in Fig 7). These categories can be imagined as models connecting the conceptual elements. Although experiments were not directly recognized in the content of the three textbooks (Feynman et al., 1964; Walker et al., 2008; Knight, 2008) for illustrating the laws of Biot-Savart and Ampère, they are widely used to explain other topics. Because prior and extended knowledge are connected through epistemic processes such as modelling and experiments, links to the resulting knowledge structures necessarily carry these processes (Mäntylä, 2011). The categories of links between conceptual elements in the content of these three textbooks are used with different frequencies, even though the topic and level of study were the same (Fig 8).

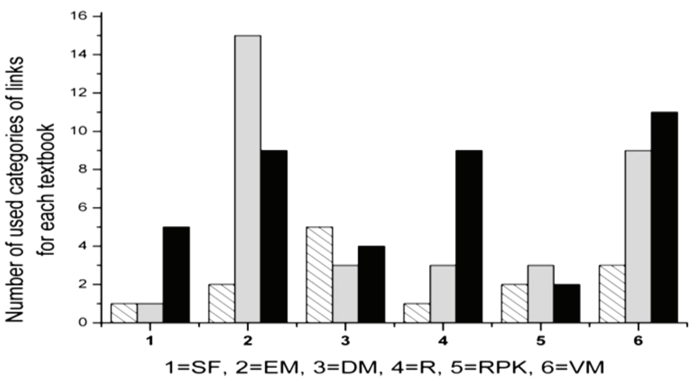

Figure 8 *The number of categories of links. Categories of links used in the textbooks of Feynman et al. appear as dashed bars, in Walker et al. as grey bars, and in Knight as black bars.*

According to Fig 8, Feynman's textbook used relatively few links, although the number of basic elements in that book was also smaller than in other books. All of the books applied the different types of links categorized in this study. The textbook by Feynman et al. emphasized descriptive models, the textbook written by Walker et al. focused on explanatory and visual models, and the textbook by Knight, which stressed explanatory and visual models and reasoning, was the most versatile.

6.4 interplay between the organization of knowledge and representation forms

Previous research has shown that there is a close connection between the SMK of teachers and their PCK (Shulman, 1986; van Driel et al., 1998; Hashweh, 2005; Abell, 2007; Rollnick et al., 2008). Teachers' SMK is stored in their long-term memory by means of organization of knowledge, which, on the other hand, contributes to the disciplinary aspects of PCK. For example, teachers with highly organized SMK can retrieve their knowledge in a shorter time and thus more effortlessly. They can probably connect different topics in a grade or similar topics in different grades more effectively. SMK addresses the totality of ReFs (Hashweh, 2005; Loughran, 2006; Rollnick et al., 2013). On the other hand, Shulman (1986) stated that teachers' PCK concern mainly their representation strategies such as analogies, explanations and examples as well as their knowledge of students' difficulties or misconceptions. Therefore, PCK employed a subset of domains of ReFs (Shulman, 1986) (see Article IV for discussions). Article II briefly investigates the relation between the organization of knowledge and ReFs. The interplay between teachers' ReFs and the organization of knowledge in terms of the four domains of the introduction and application of the laws of Biot-Savart and Ampère appear in Table 5 below.

Table 5 *Relationship of representation forms to the knowledge organization of four university teachers for each domain (numbers represent the frequency of use of the forms) (Table 6 in Article II).*

Domains	Representation forms	Knowledge organization overall
1. Introduction to Biot-Savart law	Descriptive math model: 30 %	Strongly connected
2. Application of Biot-Savart law	Explanatory math model: 63 %	Strongly connected
3. Introduction to Ampère's law	Reasoning: 30 %	Moderately connected
4. Application of Ampère's law	Explanatory math model: 35 %	Moderately connected

As Table 5 shows, teachers can construct well-organized knowledge with mathematical models for expressing the introduction and application of Biot-Savart law. But using reasoning as the major ReFs for the introduction and application of Ampère's law lead to poorly connected and organized SMK. One might have expected that using more mathematical models would have worked better here, but these results probably point out not only ReFs, but also the difficulty of the topic of Ampère's law, as we discussed in Chapter 5.2.2.

Our conceptualization of ReFs emphasizes the importance of providing categories for representing SMK in class (Geddis & Wood, 1997). The integration of these categories can apparently be achieved more easily if teachers possess a rich organization of knowledge. Since we did not examine the influence of the organization of SMK on teachers' ReFs with enough details, there remains uncertainty whether the organization of knowledge is directly linked to ReFs or not.

7 Discussions

The focuses of this thesis are on the organization of knowledge and ReFs of physics knowledge as well as on physics teachers in university and upper secondary schools with regard to the topic of magnetostatics.

This study was conducted at the University of Helsinki, Department of Physics during 2010-2013. The observation of lessons on the conceptualization of ReFs and the organization of knowledge took place in two upper secondary schools in Finland, Helsinki in 2012. The studies comprising this thesis examine each of the aforementioned notions for teachers and textbooks of magnetostatics. One of the main components of teachers' PCK refers to their use of ReFs (Geddis & Wood, 2007). Similarly, organizing concepts logically and meaningfully is an essential element of their SMK (Bransford et al., 1999). Since teachers' SMK and PCK are tightly attached as categories that form their knowledge base (Shulman, 1986; 1987; van Driel et al., 1998; Hashweh, 2005; Abell, 2007; and Rollnick et al., 2008), it is reasonable to expect ReFs and the organization of knowledge to be related.

Thus far too few studies address the SMK of teachers with regard to the topic of magnetostatics with a focus on the two subtopics of Biot-Savart law/magnetic flux density and Ampère's law (Abell, 2007). She emphasized that scholars have sought to understand the specific physics concepts rather than to investigate the organization of knowledge. Therefore, in this thesis we attempt to visualize and investigate the organization of conceptual elements of physics as discerned in either physics textbooks or teachers' views. The potential uses of such knowledge focus on how teachers' organization of knowledge can influence science education and science teacher education. However, one should notice that Ampère's law in upper secondaty schools concerns the magnetic force between two long wires, which is in contrast to the notation of Ampère's law in university level (see Chapter 5.2). Furthermore, magnetic flux density in upper secondary schools deals with magnetic force on moving charges or current carrying wires (see Chapter 6.3.2), but Biot-Savart law in university level concerns with magnetic field of moving charges and current carrying wire instead of magnetic force.

Concept maps served as a qualitative tool to depict, evaluate, and finally compare teachers' knowledge to each other. We examined the structure of the concept maps in terms of structural patterns such as loops and cycles. These patterns show how concepts are interwoven within teachers' SMK. This approach is concurrent with structural analysis of the concept maps of students (Koponen & Pehkonen, 2010). Teachers must be able to properly organize their SMK (Shulman, 1986), which assists them in representing and translating their SMK more effectively (Bransford et al., 1999). However, the results of this study (Article II) revealed that in some cases, especially the case of Ampère's law, teachers' SMK was not as well organized as the case of the Biot-Savart law. Nevertheless, their ways of organizing knowledge differed. After this study (Article II), we asked the teachers' opinion regarding their approach to constructing concept maps and visualizing their knowledge organization. Their feedback was quite positive: they stated that they use a similar ordering of concepts when teaching and preparing their teaching instructions. Although it was impossible to observe the four participating university teachers' lessons, the evidence suggests that the method presented here is capable of detecting teachers' organization of knowledge as a crucial component of their SMK. Even so, investigating the obstacles to teachers organizing the topics of Ampère's law and proposing them appropriate methods to overcome such difficulties will require more studies.

Another stage of the investigation of knowledge organization considered three university textbooks and their structural arrangements (Article I). Previous research has emphasized the impact of textbooks as curriculum materials for teaching and learning (Ball & Cohen, 1995; Davis & Krajcik, 2005). However, it appears that we need certain methods to visualize and evaluate the content of these textbooks, the way these elements are connected together, the nature of the links between concepts, the structural patterns, and their properties. By doing this, the knowledge organization of these textbooks becomes explicit. A review of the literature reveals that textbook examinations focus on their textual features (Strube, 1989) and educational goals (Orpwood, 1984; Chiapetta et al., 1993; Wilkinson, 1999). In addition, several studies have explored the coherency of text-based materials and their influence on learning (Ainsworth & Burcham, 2007; McKowen et al., 1992; Roseman et al., 2010). Therefore, this study introduces a new method for analyzing the content of textbooks with a focus on their knowledge organization (Article I). Again, concept maps are employed to depict the knowledge organization of these three textbooks. Nevertheless, the concept maps in Articles (I, II, III) differ from traditional ones where verbs are propositions. In the first three Articles, instead of verbs, models and experiments serve to bridge the concepts. Using models instead of propositions is promising for two reasons: first, concept maps that include the laws of Biot-Savart and Ampère contain a huge number of links between concepts. Second, investigations of the procedural nature of the knowledge organization of propositions are demanding or difficult.

From the results of this study, we might assume that textbooks with flexible and network-like structures would be the most influential curriculum materials in science education. The reason probably refers to learners' choice of understanding the topics in a variety of different and corrected ways. Following the conclusions of other researchers, the quality of teaching will improve if teachers successfully recognize and perceive the organization and structural patterns of curriculum materials such as textbooks (Wilkinson, 1999; Roseman et al., 2010).

To better understand the organization of knowledge used by teachers and textbooks, the author of this thesis compared the structures of their SMK (Article III). Some researches have reported striking similarities in inductive and deductive ways of organizing magnetostatics concepts. This thesis studied the relationship between the knowledge organization of university textbooks and teachers using a comparison method of analysis. This method allowed us to visualize and examine the knowledge organization of both teachers and textbooks, and to place their structural properties side by side. Here we assume that a skeleton of the knowledge organization of science disciplines can be presented through conceptual elements and links between them (Kinchin et al., 2000;

Koponen & Pehkonen, 2010). We recognized structural patterns in the SMK of teachers and textbooks, such as triangular and spoke-like structures. Triangles mirror the clustering capacity of concepts, whereas spokes reflect the deductive ability of concepts (da Costa et al., 2007).

This thesis did not explore whether teachers were aware of the similarities and differences between their own organizations and textbooks. Still, teachers' beliefs about feasible ways to present and arrange the concepts may influence their organization of knowledge. We believe that visualizing the structural arrangements of teachers' knowledge and comparing it with the knowledge organization of some reliable curriculum materials, such as textbooks, could prove beneficial in education. Teachers could enrich their SMK and enhance their pedagogical skills, including their ReFs. We contend that teachers' thoughts and beliefs affect the ways teachers and textbooks organize their SMK (Hashweh, 2005). It was impossible to determine why participating teachers rely mainly on the textbooks of Knight (2008) and Walker et al. (2008). One reason could be the popularity of these textbooks in Nordic countries as well as in the United States or that textbooks influence teachers' knowledge organization.

In principle, the choice of categories of ReFs was inspired by 1) the typology of science models suggested by Harrison and Treagust (1998), 2) the classification of physics knowledge proposed by Van Heuvelen (1991), and 3) the representation repertoire by Shulman (1986). The first one contains mathematical and theoretical models, analogical models, and models for the visualization of concepts such as figures and diagrams. The second one includes different representations such as pictorials, physical models, mathematical models, and words. The last one includes representational strategies such as analogies, examples, and explanations. These forms motivated us to categorize the links between conceptual elements through teachers' interviews (Article II) and the content of textbooks (Article I). The structural arrangements of teachers' SMK about Ampère's law were not as well organized as the Biot-Savart law. Since mathematical models were applied more in cases of the introduction and application of Biot-Savart law and were better structured, mathematical models may prove helpful for more organized knowledge. The organization of teachers with regard to introducing Ampère's law had many dead-ended concepts, which were disconnected from the rest of the map. Since conceptual elements regarding the introduction to Ampère's law were loosely connected, if mathematical models would have replaced reasoning, one might expect better outcomes for the organization of knowledge.

Categories of ReFs, which emerged from the analysis of the observed lessons in Article IV, function as different forms that teachers employ to translate their SMK. These forms can be illustrated in two dimensions of the character of discourse and the medium of instruction, as expressed in Chapter 6.3.1.

This study showed that teachers combine these categories and perform in a contextually bound manner (e.g. in the context of magnetostatics). The categories recognized in Articles I, II, and IV are parallel to each other. However, one should note that these categories are not exclusive, since they are drawn from limited data. In Article I, our data are confined to only three university textbooks; in Article II, our data are limited to four university teachers; and in Article IV, we were restricted to two case studies of upper secondary school teachers. Still, the potential to identify teachers' ReFs, their organization of knowledge, and how qualitative and some quantitative methods of analysis integrate these facets is evident. However, what makes Article IV interesting is the way in which different methods (online questionnaire, classroom observation, and concept maps) are triangulated. This provides us with more insight into teachers' SMK and PCK as a whole.

Chapter 6.4 discusses the notion of which teachers' organization of knowledge and ReFs are bound together. We believe that if teachers possess rich and well organized SMK, they can more effectively convey that knowledge through ReFs. The need to possess certain ReFs to translate one's SMK in the classroom could be understood from the study by Geddis and Wood (2007). It is important to bear in mind that most appropriate ReFs could be recognized from studies conducted on specific topics: "in our view the value of PCK lies essentially in its relation with specific topics" (van Driel et al., 1998). Meanwhile, PCK is at the core of teachers' knowledge base, and SMK – especially its organization – should receive emphasis in science teacher education.

7.1 Validity and reliability of the research

To ensure the validity of the categorization of the links between the conceptual elements in the content of the textbooks, four reviewers judged the categories based on questionnaires, which we provided for them (Article I). These reviewers were university teachers at the University of Helsinki, Department of Physics. The questionnaires covered two topics and concerned their textbooks. The reviewers reported their agreements with the categories using a five-point Likert scale (5 = Strongly agree, 4 = Agree, 3 = Neither agree nor disagree, 2 = Disagree, 1 = Strongly disagree). Teachers could comment on the categories and, in case of disagreements, pose other categorizations. To analyse the results of the responses to the questionnaire, we used two statistical indices: mean values and standard deviation. Our investigations showed that although employing these two statistical indices for Likert-scale questions is somewhat uncommon, reliable studies nevertheless recommend using them (Carfio & Perla, 2008). The results of the analysis of the mean values and standard deviations indicated that the proposed categorization, and thus the method of recognizing conceptual elements and links between them, was good.

The same teachers who participated in the questionnaires about Article I were interviewed one year later in order to investigate about their organization of knowledge and ReFs for the laws of Biot-Savart and Ampère. In Article II, extracts of the teachers' statements as recorded in the transcripts of their interviews were used to recognize the ReFs. To ensure the trustworthiness of the research, the results of the analysis were compared to a similar analysis of a colleague. The author of this thesis and her colleague discussed any disagreements until they reached consensus (Kvale, 1996). Both researchers focused on emerging categories of ReFs in each statement in a parallel way (Miles & Huberman, 1996). As mentioned earlier, the four videotaped interviews had consistency values of the identified categories between them ranging from 75% to 80%: 75% David, 78% John, 80% Nigel, and 79% Chris (Articles II and III). To ensure the reliability of the research, the results were ultimately triangulated through interpretations and categorizations.

As we mentioned earlier, interviewed teachers had an opportunity to select from the concept list provided for them. However, teachers could add or ignore the provided concepts at their liberty. The idea of providing a concept list fits the "construct the map technique" proposed by Ruiz Primo and colleagues (2001). In Articles II and III, the SMK of teachers and textbooks regarding magnetostatics were classified into four domains: 1) Introduction to Biot-Savart law, 2) Application of Biot-Savartlaw, 3) Introduction to Ampère's law, 4) and Application of Ampère's law. This clarification was adopted based on Oser and Baeriswyl (2001), who claimed that teaching steps should be sequenced in this fashion. Besides, these stages are quite applicable to concept building. Next, the data were analyzed with respect to these four domains.

We evaluated the structural patterns and their characteristics using the same network observables such as hierarchy and clustering. Finding the characteristics of other observables, such as the centrality and density of links, could be easily perceived: in many cases, Biot-Savart and Ampère were at the Centre of the graphs, so they contained the most attached links. On the other hand, teachers had quite enough teaching experience, and the textbooks were typical, standard university textbooks used worldwide. Therefore, we can imagine that the obtained structures and their observables were accurate, valid, and correct (Ruiz Primo et al., 2001). In Article III, in order to detect the interconnections between the conceptual elements, we used structural observables of clustering. Due to the definition of clustering, the degree of connectivity is described in terms of triangles representing three concepts (da Costa et al., 2007). Therefore, we considered only conceptual loops containing three concepts. Longer loops indicating cross reference-type connections were ignored in Article III. Also it was worthy if we could conduct some interviews to develop an awareness of teachers' opinions about the similarities and differences between the organization of their own SMK and that of their textbooks. In 90% of the cases in Article II, the recognized loops and cycles embraced either Biot-Savart law or Ampère's law. To strengthen the reliability of the analysis in Article III, we tried to consider only those cases which covered these topics.

In the last Article IV, author of this thesis first identified the ReFs for the magnetic flux density of moving charges and conductive wire, and Ampère's law. Next, the second author double-checked the reported results, and finally reached consensus. However, a parallel analysis may have strengthened the validity of the research.

7.2 Implications for teaching and learning

By examining the organization of teachers' SMK and their ReFs as a part of their PCK, similarities as well as clear differences between their organizations have become apparent.

Thus, one can use the proposed tools, such as concept maps and structural patterns, to see these differences. These differences can then be measured with structural observables such as hierarchy and clustering or structural properties such as the number of dead-ended concepts, cycles, and loops. All stages of this study cover the crucial topics of magnetostatics with a focus on the Biot-Savart law, which is known as magnetic flux density in upper secondary schools, and Ampère's law. Following the argument of van Driel (1998), investigations of teachers' PCK should be topic-specific. Therefore, one must be careful to generalize the results of this study. In other words, similarities and differences between the ways teachers organize and translate their SMK vary between subjects (e.g. thermodynamics, mechanics, etc.) and between disciplines (e.g. biology, chemistry, etc.). The results indicate that teachers face certain obstacles or challenges in arranging and representing Ampère's law. This could reflect the importance of SMK and its noticeable influence on teachers' knowledge base, specially their PCK. In conclusion, we believe teachers' SMK, PCK, their organization of knowledge, and ReFs are contextually bound together.

Conceptual elements are at the core of learning, and the ways these elements connect to each other are also important in understanding the topics. The reason is that links between concepts inform us about the meaningful structural patterns within knowledge (Bransford et al., 1999; Mäntylä, 2011). As a result, learning the content knowledge of physics includes learning about concepts, the way they are constructed, and, finally, their organization, which forms during knowledge construction. Highly organized knowledge has many applications for teaching and learning, and can be achieved with less effort and time. Teachers use of highly organized knowledge in classrooms develops fluency in students' learning (Schneider & Shiffrin, 1977).

Studies of science textbooks show that the organization of the content of textbooks significantly affects students' learning (Koulaidis & Tsatsaroni, 1996). Although the organization of knowledge in textbooks mirrors the authors' choice, this choice still has sequences for how students understand or learn the content. One could argue that if the content knowledge of a textbook has a clear and simple structure, the number of ways to understand and organize the knowledge, from the learners' point of view, is therefore limited. Remembering and recovering that kind of knowledge seems demanding: a learner failure to understand one concept then hinders the learner's understanding of other follow up concepts. As a result, the whole knowledge structure will collapse. In contrast to simple structures, textbooks with flexible and interconnected structures provide learners with several options to arrange their own knowledge: as a result, accessing knowledge will be less demanding. If one fails to understand one concept, other possible links and connections are available to understand the target concept. We assert that an explicit structure for textbooks may not necessarily have a visible impact on students' learning. But textbooks with flexible structures can serve in various ways in teaching and learning. Comparing the knowledge organization of teachers and textbooks of the Biot-Savart law and Ampère's law revealed both similarities and differences. The similarities revolve around shared triangular and spoke-like structures. Triangular structures reflect the inductive characteristics of knowledge structures where concepts tie together. Spoke-like structures mirror the deductive properties of knowledge structures where concepts are ordered hierarchically. Emphasizing the structures shared between textbooks and teachers could reveal meaningful relationships between the conceptual elements of magnetostatics. Therefore, as Bransford and colleagues posited (1999), focusing on such structures not only improves the teaching and understanding of different topics, but could also reveal how much of teachers' knowledge depends on or is drawn from textbooks. According to the results of this study, especially in Article III, teachers and textbooks in some cases organize their SMK differently. Since these textbooks are standard and widely used in universities, and because these teachers were experts with sufficient teaching experience, all the organizations and relations they made can be considered valid and reliable. Therefore, sharing thoughts and more frequent collaboration between university and school teachers is recommended. By doing so, they can become aware of many different ways to arrange the core concepts, familiarize themselves with different meaningful structural patterns, and ultimately enrich their teaching instructions and plans. The issues mentioned above are expected to influence teachers' SMK and, as a result, their PCK. Meanwhile, differences between the organization of knowledge in textbooks remind teachers to rely on different resources for their teaching purposes; they should familiarize themselves with multiple ways to represent their SMK. This thesis could offer some advantages to pre-service teachers who do not yet possess the same potential as expert teachers do. The methods proposed in this study can enhance pre-service teachers' ability to prepare their teaching, to build their SMK around the key concepts and to arrange them properly.

7.3 Practical applications of this research

The approach of this study can be used inside classrooms first in pairs and then in groups. The teacher can provide explicit instruction and practice about how to make knowledge organization patterns and how to evaluate and analyze them. Students may start organizing their knowledge of a specific topic either by selecting either their own proposed concepts or concepts from a list provided by the teacher. If students work in pairs, one can select the concepts, connect them, and justify the connections and reasons between them. The other student, the listener, can take brief notes and ask for possible clarifications and further reasons for connecting the concepts (see Van Heuvelen, 1991). After a specific time, each pair possesses a structural pattern that includes concepts and links between them, so they could share their ideas with other pairs and compare their thoughts about the nature of the links and structural patterns. During discussions, students can recognize the mutual structural arrangements, such as spokes and triangles, discussed in this study. If necessary, the teacher should provide further explanations about the meaning of those structures, correct students' misconceptions, help them to deepen their understanding of the links between concepts, collect the mutual structures between pairs, and record them. At the end of the task, the teacher could present her/his own constructed map, which other colleagues may have validated in advance. Next, the teacher can assess students' organization of knowledge in different ways, such as by categorizing them into three categories: non-learning, surface-learning, or deep-learning (Hay et al., 2008). Later teachers can develop their teaching on the basis of students' structural patterns, which is a good example of students' prior knowledge.

We believe this task can help students to become active participants in constructing concepts, justifying the relationship between concepts, sharing thoughts, and reflecting on and evaluating their thinking. Moreover, using this task as a formative assessment will create a beneficial and challenging learning environment for collaboration not only between students, but also between students and their teacher.

8 Conclusions

The results show standard university physics textbooks which are in frequent used at introductory levels (Knight, 2008; Walker et al., 2008) have more or less similar SMK and structures. However, less popular textbooks, such as the Feynman Lectures on Physics (Feynman et al., 1964), differ somewhat in terms of content and structure. Although these three textbooks share the main conceptual elements, Feynman employs some advanced concepts such as Maxwell's equation, Stokes' theorem, and vector potential. The other two textbooks emphasize different examples and applications of the studied laws, such as the magnetic field of different systems (Solenoid, Loop, Coil, Toroid, inside and outside of a straight and long wire, Brain). The structure of Feynman was clear and simple, while the other two textbooks featured more flexible and complex organizations.

The overall SMK of university teachers of both the introduction and application of Ampère's law were not as well structured as for Biot-Savart's law. The results of the current study indicate that conceptual elements of Biot-Savart law are more clustered and show inductive-like properties. However, for the case of Ampère's law, concepts of magnetostatics tend to become hierarchically ordered and show deductive-like characteristics. Our investigations reveal differences between the organizations of knowledge of four university physics teachers, between three university physics textbooks that the teachers use for their teaching purposes, and between those teachers and their textbooks.

For the knowledge organization of upper secondary school teachers, the highest priority in which to order concepts of magnetostatics is: magnetic field, field lines, the right hand rule, electric current, a wire carrying current, and the magnetic field of a coil and long wire.

Content analysis of the university teachers' interviews revealed a variety of ReFs, including models and experiments. Models include descriptive and explanative math models, visual models, analogies, reasoning, and statements of facts. The identified categories of ReFs for upper secondary school teachers were stating, explaining, or describing models (analogies, descriptive mathematical models, and descriptive visual models), facts, the relationship between experiments and mathematics, appropriate questions, examples from everyday life, and difficulties in physics.

In contrast to mathematical models, which were predominant in introducing the Biot-Savart law and explaining its applications and examples, reasoning played an important role in introducing Ampère's law. The teachers' knowledge arrangements were better organized for the cases involving the introduction and application of Biot-Savart law (domains 1 & 2) than for Ampère's law (domains 3 & 4).

For the case of uppersecondary school teachers, ReFs can be expressed within two dimensions: "forms of discourse" such as State, Explain, and Describe as well as "medium of instruction". The recognized items within the "medium of instruction" are not exclusive and contain the facts, the relation between experiment and mathematics, appropriate questions, everyday life examples, difficulties in physics, and models (analogies, descriptive visual model, and descriptive mathematical model).

The most important concepts in the context of magnetostatics were magnetic field and magnetic fields of different systems, including long wire and current loop, symmetry, Ampère’s loop, Coulomb’s law, and charge. The concepts shared in the content of the three university textbooks for introducing and explaining the laws of Biot-Savart and Ampère were magnetic field, the magnetic field of a long wire, Gauss’s law, and the magnetic field of a solenoid. However, the other two textbooks prevalent at introductory university levels shared even more concepts: the magnetic field inside a wire, the magnetic field of a current loop and coil, and superposition principles. The concepts of magnetic field, the magnetic field of a long wire, and current loop were therefore prominent in the SMK of not only teachers, but also textbooks. As a result, the concepts of magnetic field and the magnetic field of a long wire were both emphasized at university and upper secondary school educational levels.

The brief analysis of relationship between knowledge organization and ReFs indicate using representation form (ReFs) of reasoning does not lead to well-organized SMK. However, using ReFs of mathematical models lead to well-ordered knowledge.

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